Long-Term Trends in Benthos Abundance and Persistence in the Upper Sacramento-San Joaquin Estuary

Summary Report: 1980-1990

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California Department of Water Resources
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U.S. Geological Survey
U.S. Enironmental Protection Agency

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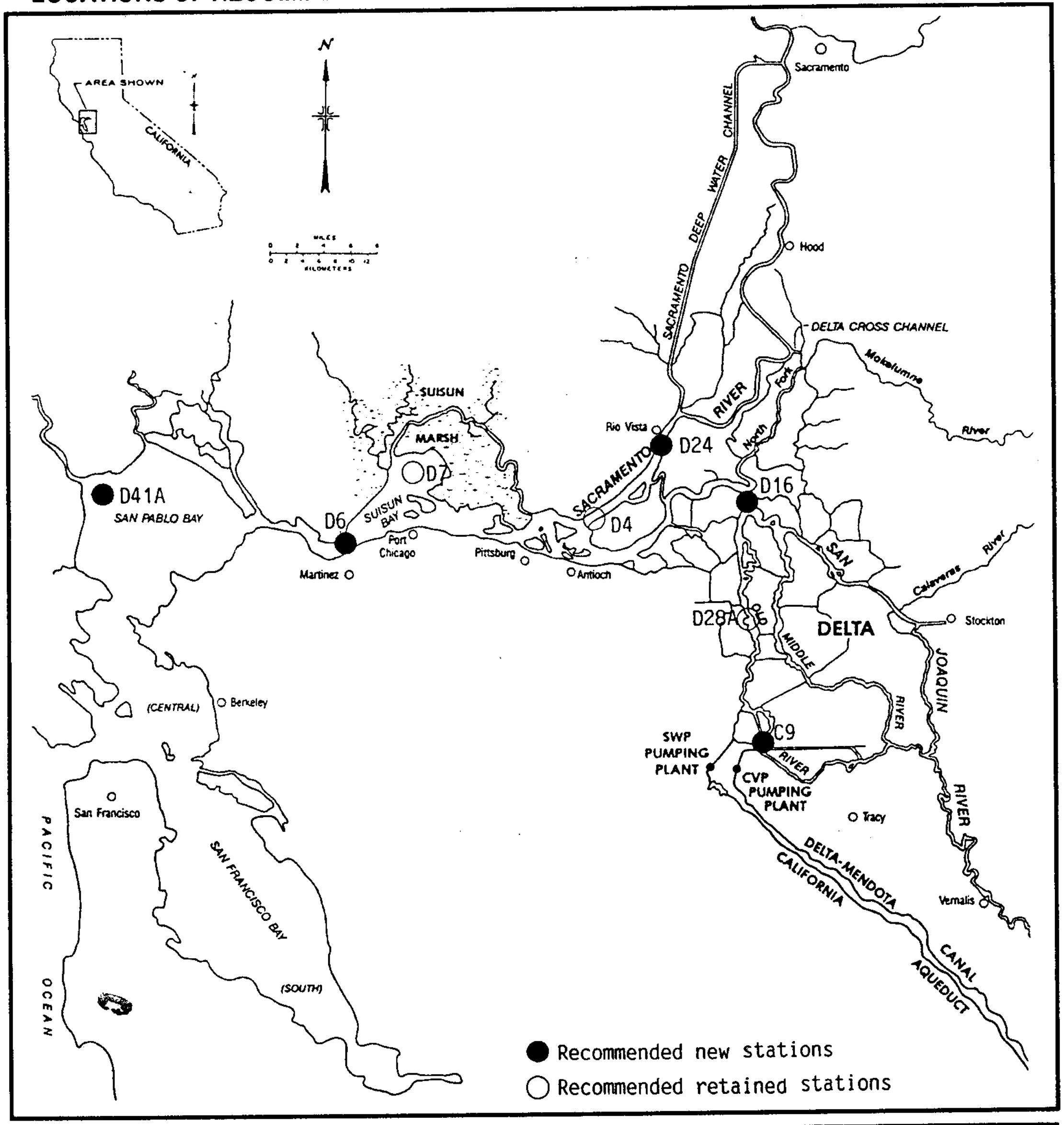
CONCLUSIONS

A variety of analyses were used to summarize long-term trends in the benthos and relevant physical, chemical, and biological variables of the upper Sacramento-San Joaquin estuary. Results of these analyses were compared and related to determine probable causes for the trends in the benthos. The main conclusions from this effort are:

- The exotic organisms *Potamocorbula amurensis*, *Hemileucon hinumensis*, and *Gammarus daiberi* all became established as numerically dominant organisms at one or more benthic sampling sites in the upper estuary between 1980 and 1990. Establishment and numerical dominance of these exotic species has altered the ecology of the upper Sacramento-San Joaquin estuary.
- The combination of extreme deviations in freshwater flows and salinity along with the invasion of three introduced species resulted in a substantial change in the benthic communities at stations D7 and D4. These communities are now dominated by one or more of the recently introduced species.
- The more eastern stations (D11, D19, D28A) were also affected by the physicochemical changes and establishment of exotic species, although to a lesser degree than D7 and D4. The benthic communities at these eastern stations were apparently able to absorb these changes, since the communities did not show a substantial change in persistence of resident species.
- From 1980 through 1990, there was a general increase in the amount of fine sediment at many of the sampling locations as a result of reduced streamflow. In general, however, there was no connection between trends in sediment composition and the abundance and persistence of benthic organisms.
- From 1978 through 1990, concentrations of volatile suspended solids showed no significant trend with time, although there was a substantial decline in Suisun Bay. Phytoplankton and zooplankton biomass showed significantly negative trends in many parts of the upper estuary. In Suisun Bay beginning in 1986, Alpine and Cloern (1992) found a sustained and substantial decline in phytoplankton biomass that could be at least partly explained by the invasion of the suspension-feeding Asian calm, *Potamocorbula amurensis*. A similar phenomenon may have occurred in the western Delta.

LOCATIONS OF RECOMMENDED NEW AND RETAINED BENTHIC MONITORING STATIONS



NUMBER, LOCATION, AND RATIONALE FOR FIVE NEW BENTHIC MONITORING STATIONS

Station Number	Station Location	Rationale for Selection
D41A	Light 2, Mouth of Petaluma River, San Pablo Bay	Only site in San Pablo Bay. USGS and DWR have sampled site since 1988. Routine sampling could provide information relating benthos in San Pablo Bay to benthos in Suisun Bay.
D6	Ship channel in Suisun Bay near Martinez	Provides better spatial coverage of Suisun Bay. Samples a habitat different from site D7 in the Grizzly Bay shoal area.
D24	Sacramento River below Rio Vista Bridge	Provides better characterization of lower Sacramento River area.
D16	San Joaquin River at Twitchell Island	Provides information on the benthos of the lower San Joaquin River.
C9	West Canal opposite Intake Channel to Clifton Court Forebay	Permits better spatial coverage for assessment of potential water project related impacts to the benthos.

RECOMMENDATIONS

The premise of these recommendations is that a benthic monitoring program is needed in the upper Sacramento-San Joaquin estuary with the following objectives:

→Monitor trends in the abundance and distribution of benthic fauna.

→Detect major changes in species composition, especially introductions.

→Provide baseline information for special studies.

Given the stated objectives and results from the various analyses, a benthic monitoring program with the following attributes is recommended:

- Benthic and sediment sampling should continue at three existing sites: D7-C, D4-L, and D28A-L. Sampling at the other five existing sites (D11-C, D4-R, D4-C, D19-C, D28AR) could be discontinued. Instead, five new sampling stations should be established. Sampling these stations provides better spatial coverage of the monitoring area and may permit a better understanding of SWP and CVP related impacts in some cases.

- Three replicate samples should be collected from each site on a monthly basis. This level of sampling effort would result in a monitoring program that is consistent with all program objectives. All other sample collection methods could remain the same.

- Organism biomass should be estimated bimonthly at all sites by measuring total wet weight of major taxonomic groups (*eg,* phylum or class) and dominant species. Existing curves relating tissue weight to total weight could be used for organisms, such as clams, with a substantial portion of their total weight arising from nonliving parts. All other sample analysis methods could remain the same. Routine measurements of both biomass and abundance would permit estimates of benthic production. In addition, biomass estimates provide information useful to understanding benthic trophic dynamics.

- A summary analysis and full re-evaluation of the benthic monitoring program should be completed every 5 years. Annual analyses should continue to determine if program adjustments are necessary.

ACKNOWLEDGMENTS

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Chapter 1

INTRODUCTION

The Department of Water Resources began monitoring the soft-bottom benthos of Suisun Bay and the Sacramento-San Joaquin Delta in 1975 as part of a comprehensive environmental monitoring program mandated by the State Water Resources Control Board. The resulting program has produced a comprehensive data set, which is used in a variety of ways including routine examination of benthos abundance and distribution, detection and tracking of introduced organisms, and as baseline information for applied research projects.

This report begins with a review of the benthic monitoring program — its origin, purpose, and design criteria. The study area is then described, including a discussion of trends in relevant physical, chemical, and biological variables. Next, the results of summary analyses for benthic monitoring data collected from 1980 through 1990 are presented. These results are also related to trends in other relevant variables to discover causal relationships. Results of analyses that test the detectability and sensitivity of the monitoring methods are also included.

Program Origin

The benthic monitoring program is one element of a comprehensive baseline monitoring effort required of DWR by the SWRCB through its regulatory authority over California's water rights. The program also includes monitoring of water quality, phytoplankton, and zooplankton. Monitoring and reporting requirements of the program are described in the current Water Right Decision 1485[1].

Water Right Decision 1379[2] (which preceded Decision 1485) was the first delta water right decision to provide terms and conditions for a comprehensive monitoring program. As a result of testimony presented during hearings for Decision 1379 and testimony heard in earlier decisions (Decisions 990 and 1275), SWRCB decided a monitoring program was needed to routinely determine water quality conditions, pollutant loads and sources, and changes in environmental conditions within the estuary.

The environmental monitoring program described in Decision 1379 was developed by Stanford Research Institute through a contract with SWRCB[3]. SWRCB's stated objective was to:

> "develop a monitoring program sensitive to important parameters that characterize the environment, and that can provide information necessary for effective management of the water resources of the region".

The resulting program was truly comprehensive in scope, as it considered a wide variety of impacts to the estuary. The report's inventory of potentially affected resources, combined with the sources of impact (Table 1), formed both the rationale and the basis for the environmental monitoring program.

Table 1
SOURCES OF POTENTIAL IMPACT TO THE INTEGRITY OF THE UPPER ESTUARY AND RESOURCES POTENTIALLY AFFECTED

Sources of Potential Impact	Resources Potentially Affected
Sea Water Contamination	Municipal Water Supply
Pesticide Manufacture & Application	Industrial Water Supply
Irrigation Return Water	Agricultural Water Supply
Domestic & Industrial Waste Water	Fish and Wildlife Propagation & Sustenance
Breakdown Products	Commercial & Sport Fisheries
	Navigation
	Recreation
	Esthetic Values (including historic value)

SOURCE: Weisbecker *et al* 1970.

1 State Water Resources Control Board. 1978. *Water Right Decision 1485 for the Sacramento-San Joaquin Delta and Suisun Marsh.* 44 pp.
2 State Water Resources Control Board. 1969. *Water Right Decision 1379 for the Sacramento-San Joaquin Delta and Suisun Marsh.*
3 LW Weisbecker, JL Mackin, AW Knight, RW Brocksen. 1970. *An Environmental Monitoring Program for the Sacramento-San Joaquin Delta and Suisun Bay.* Stanford Research Institute. Contract 9-2-32. Prepared for State Water Resources Control Board. Publication 40. 106 pp plus appendixes.

In its report, SRI recommended full implementation of a comprehensive environmental monitoring program to ensure that collection and interpretation of environmental information was sufficient for effective management of the estuary. SRI found very few estuary monitoring programs existed at the time of the review. Although numerous applied research projects had been completed, these investigations were conducted by several agencies working without a common objective or plan to investigate or manage the estuary. SWRCB had committed itself to such a monitoring program and used its powers in the water right decision process to implement a program that went beyond measuring changes in the estuary that might be directly related to water project operations.

SRI's review of existing monitoring programs also disclosed a lack of routine monitoring for biological constituents. The authors concluded that:

> "as the relationships between physical, chemical, and biological conditions, and environmental effects become better defined, many more resource management actions that are directly concerned with water quality will be based upon environmental parameters. Aquatic organisms do not have the capability of processing or preconditioning water to meet their biological requirements as does man. Therefore, these organisms can be sensitive indicators of environmental change".

The SRI environmental monitoring program included monitoring benthic species abundance and diversity primarily to detect the effects of wastewater discharges on the estuary. Although such discharges are not part of water project activities, there may be secondary relationships between water project exports and wastewater discharges that could affect the estuary environment. Distinguishing the primary and secondary impacts of water project operations was an important objective of the SRI monitoring program.

Implementation of the program began in 1972, as SWRCB, DWR, and USBR met to define their individual responsibilities for various elements of the monitoring program[4]. Benthic monitoring began in 1975. Benthic sampling frequency of once a month, as recommended by SRI, was modified to quarterly in Decision 1379 and then biannually in Decision 1485.

Program Description

Implementation of the benthic monitoring program in 1975 coincided with numerous other changes in the comprehensive monitoring program. The most notable change was the transfer of overall responsibility for the monitoring program from USBR to DWR. Initially, the majority of DWR's resources were directed toward implementation of the water quality monitoring element, because it was agreed that a program of this magnitude would have to be phased in over a reasonable period[5]. Once the routine of the water quality monitoring element was established, the benthic monitoring element was implemented essentially as described in Decision 1379. However, it was agreed in discussions during program implementation that: (1) samples would be collected biannually rather than quarterly, and (2) the number and location of sampling stations detailed in Decision 1379 would be adjusted. Initially 11 of the 16 benthic stations listed in Decision 1379 were sampled (Table 2).

In 1978, SWRCB released Decision 1485, which (as in Decision 1379) described the benthic monitoring element requirements. Although the basic requirements remained unchanged from Decision 1379, several changes were made in the number and location of sampling stations, as summarized in Table 3. These changes were based on results of data analysis and field experience gained from sampling in previous years. From 1975 through 1979, between 11 and 16 stations were sampled biannually for benthic species composition and abundance and sediment composition. These data on species presence, abundance, and distribution were used to characterize the delta's benthic environment and assess its benthic populations. DWR reported and evaluated these monitoring results in annual summary reports[6].

4 Harlan Proctor, DWR; personal communication.
5 H. Proctor; personal communication.
6 Department of Water Resources. Annually, 1976 to Present. *Water Quality Conditions in the Sacramento-San Joaquin Delta.* Report to the State Water Resources Control Board in accordance with Water Right Decision 1485 [Decision 1379 until the 1979 report], Order 4(f).

In June 1980, DWR began monthly collections of benthic and sediment samples at five stations in the upper estuary (Figure 1). This change in sampling design was made "to more accurately monitor and evaluate seasonal changes in the composition of the benthic fauna and associated physical factors"[7]. The five stations were selected primarily on the basis of salinity and substrate criteria (Table 4). Monitoring results from the revised program continued to be reported annually. In addition, a summary report was prepared by Markmann[8], in which she analyzed the benthic data collected from 1975 through 1981.

Table 2
INITIAL FATE OF BENTHIC MONITORING STATIONS ORIGINALLY LISTED IN DECISION 1379*

Station	Fate
Big Break off Jersey Island	Sampled, Designated D14A
Carquinez Strait at Martinez	Sampled, Designated D6
Hog Slough	Sampled; Relocated to MD6, Sycamore Slough
Middle River at Victoria	Never Sampled
Mokelumne River, South Fork near Terminous	Sampled, Designated MD7
Old River at Palm Tract	Sampled, Designated D28A
Sacramento River upstream of Confluence of American River	Never Sampled
Sacramento River at Chipps Island	Sampled, Designated D10
Sacramento River at Greens Landing	Sampled, Designated C3
Sacramento River just below Sacramento	Never Sampled
Sacramento River at Threemile Slough	Sampled; Relocated to D24, Sacramento River below Rio Vista Bridge
San Joaquin River at Mossdale	Sampled, Designated C7
San Joaquin River below Stockton	Sampled, Designated P8
San Joaquin River at Threemile Slough	Never Sampled
San Pablo Bay off Hercules in Dredged Channel	Never Sampled
Suisun Bay at Port Chicago	Sampled; Relocated to D8, Suisun Bay off Middle Point near Nichols

* Adapted from Water Right Decision 1379. (SWRCB 1969)

Table 3
STATIONS AND SITES OF BENTHOS AND SUBSTRATE SAMPLING, 1975-1981

Station	Site*	1975	1976	1977	1978	1979	1980	1981
C3	R	B	S	S	S/B	S/B		
	C	B	S/B	S/B	S/B	S/B		
	L	B	S	S	S/B	S/B		
C7	R	S	S/B	S/B	S			
	C	S/B	S/B	S/B	S/B			
	L	S	S/B	S/B	S			
D4	R	S	S	S/B	S/B	S/B	S/B	S/B
	C	S/B	S/B	S/B	S/B	S/B	S/B	S/B
	L	S	S	S/B	S/B	S/B	S/B	S/B
D6	R	S/B	S/B	S/B	S			
	C	S/B	S/B	S/B	S/B			
	L	S/B	S/B	B	S			
D7	R			S/B	S	S		
	C			S/B	S/B	S/B	S/B	S/B
	L			S/B	S	S	S	S
D8	R	S	S					
	C	S/B	S/B					
	L	S	S					
D9	R			B	S/B	S		
	C			S/B	S/B	S/B		
	L					S		
D10	R	S	S/B					
	C	S/B	S/B					
	L	S	S/B					
D11	R		S/B	S/B	S/B	S	S	S
	C		S/B	S/B	S/B	S/B	S/B	S/B
	L		S/B	S/B	S/B		S	S
D12	R	S	S					
	C	S/B	S/B	B				
	L	S	S					
D14A	R	S	S/B	S/B	S	S		
	C	S/B	S/B	S/B	S/B	S/B		
	L	S	S/B	S/B	S	S		
D19	R			S	S/B	S	S	S
	C			S/B	S/B	S/B	S/B	S/B
	L			S	S/B	S	S	S
D24	R	S	S	S				
	C	S/B	S/B	S/B				
	L	S	S	S				
D26	R	S	S/B	S				
	C	S/B	S/B	S/B				
	L	S	S/B					
D28A	R	S/B	S	S/B	S/B	S/B	S/B	S/B
	C	S/B	S/B	S/B	S/B			
	L	S	S	S/B	S/B	S/B	S/B	S/B
MD6	R	S	S/B	S	S	S		
	C	S/B	S/B	S/B	S/B	S/B		
	L	S	S/B	S	S	S		
MD7	R	S	S	S/B	S/B	S/B		
	C	S/B	S/B	S/B	S/B			
	L	S	S	S/B	S/B	S/B		
P8	R	S	S	S	S/B	S/B		
	C	S/B	S/B	S/B	S/B			
	L	S/B	S	S	S/B	S/B		

S = Substrate Collected; B = Benthos Collected
* Facing downstream: R = Right Bank, C = Center, L = Left Bank

7 DWR, Annual Report for 1980, cited.
8 C Markmann. 1986. *Benthic Monitoring in the Sacramento-San Joaquin Delta; Results from 1975 through 1981*. Interagency Ecological Study Program Technical Report 12. Department of Water Resources.

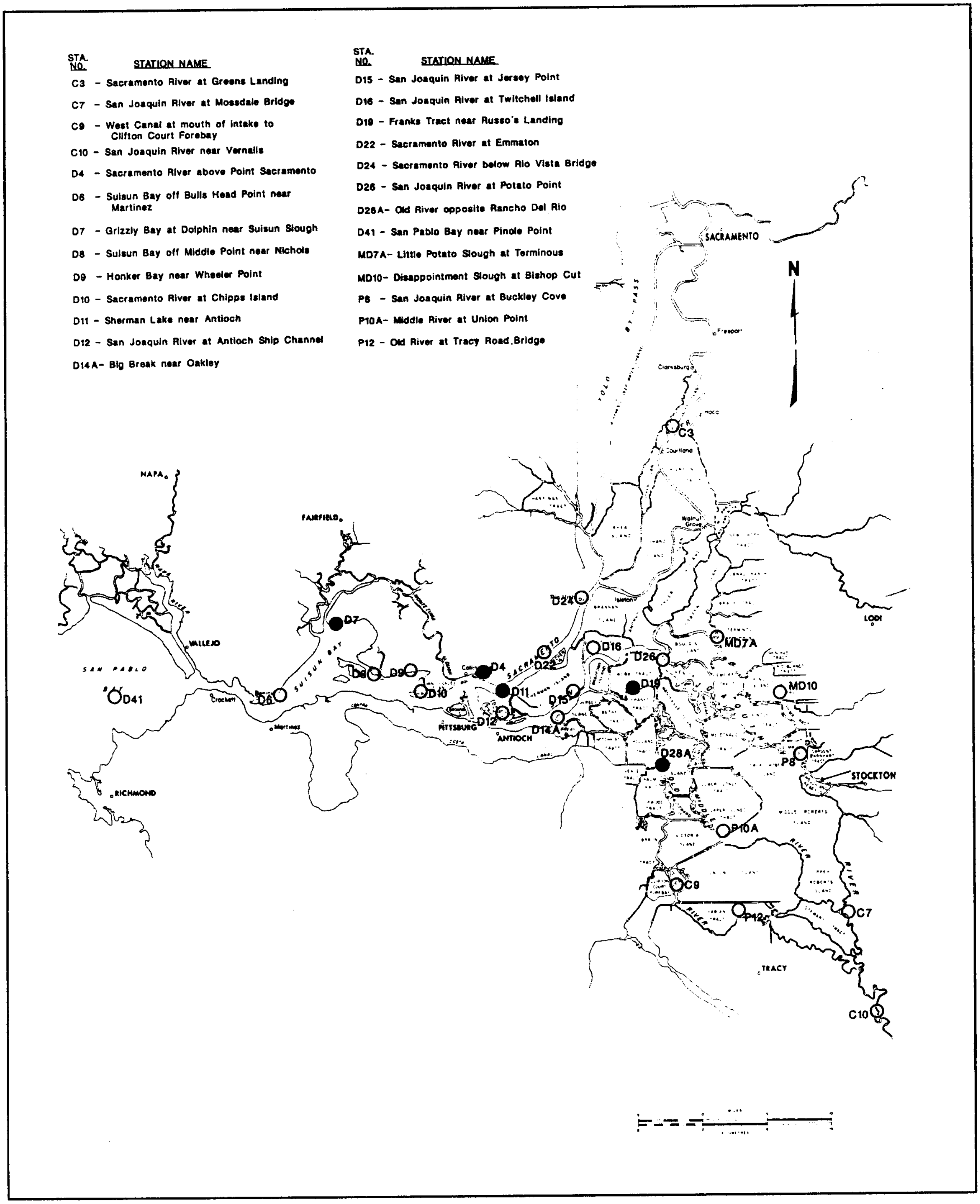

Figure 1
BENTHIC AND WATER QUALITY MONITORING STATIONS
The Five Benthic Stations are Shown as Solid Circles

Table 4
CHARACTERISTICS OF FIVE MONTHLY BENTHIC SAMPLING STATIONS

Average Depth* (Feet)	Comparative Current Velocity	Salinity Range	Substrate Composition	Selection Criteria
Grizzly Bay at Dolphin (D7)				
7	Slow	Highly variable. Specific conductance may range from 200 to 20,000 uS/cm in a year. May vary by one order of magnitude within a month.	Very stable. 8% organic material and 99% fines (silt and clay) typical.	This large, shallow embayment of Suisun Bay is subject to the seasonal influence of downstream saline water and upstream fresh water. Chosen for extreme salinity fluctuations.
Sacramento River above Pt. Sacramento (D4)				
38 (C) 11 (L/R)	Very Rapid Moderate	Freshwater outflow in winter through spring. Salinity increases in summer through fall. Specific conductance ranges from 200 to 8,000 uS/cm.	Center channel scoured; mostly sand. Banks variable. Mixed composition of sand, fines, and organic material.	Selected for effects of high current velocities on benthic fauna and for comparison of deep channel to bank conditions.
Sherman Lake near Antioch (D11)				
8	Slow	Variable, but specific conductance generally remains below 3,000 uS/cm.	Stable. 70% fines and 8% organics typical. Edges contain more sand.	Large shallow flooded tract removed from high channel velocities. Seasonally brackish, but more stable than D7.
Franks Tract (D19)				
8	Slow	Stable. Specific conductance rarely above 500 uS/cm.	Very stable. High in fines and organic material. Edges have more coarse substrate.	Shallow, flooded tract. Chosen for freshwater environment.
Old River opposite Rancho del Rio (D28A)				
18	Rapid to moderate (L) Slow to moderate (R).	Stable. Specific conductance rarely above 300 uS/cm.	High sand content, 60% on left bank. 70% fines and 30% sand on right bank.	Natural approach channel to Clifton Court Forebay. Chosen for potential impact by project operations.

*Average depth of water at high slack tide. Facing downstream, C = center, R = right bank, L = left bank.

Environmental Setting

The upper Sacramento-San Joaquin estuary is an area of complex hydrology and aquatic habitats. Tidal and river flows meet and mix in the region's channels, flooded land tracts, and bays to produce a wide range of benthic water quality and sedimentation features. The mixing of sea water and fresh water, as well their flora and fauna, occurs in the estuary's entrapment zone, which is normally located in the Suisun Bay area. The water mass of the entrapment zone, as defined by the location of surface salinities of about 1 to 6 ppt, continually sweeps across the benthic habitat of the area with the changes in tidal direction, exposing the infauna to wide shifts in salinity several times a day.

The reaches of the estuary above and below the entrapment zone provide seasonally predictable bay and freshwater benthic habitats. However, all of the estuary's benthic regions are subject to inter-annual habitat variability as outflows and water quality fluctuate with the climate and cycles of wet and dry water years. Aldrich[9] reported on seasonal changes in the species composition and abundance of benthic invertebrates from his 1955 benthic surveys of

9 FA Aldrich. 1961. Seasonal variations in the benthic invertebrate fauna of the San Joaquin River estuary of California, with emphasis on the amphipod *Corophium spinicorne* (Stimpson). *Proc Acd Nat Sci Phil* 113:21-28.

two San Joaquin River stations near Antioch and upstream at Bradford Island. The surveys were conducted in May and August to represent the periods of high and low freshwater outflows, respectively. Between the high and low freshwater flow periods, Aldrich found only slight changes in the presence and absence of species at each station. During the two surveys, the average maximum chloride content (ppm) varied by a factor of about 80 at Antioch and about 30 at Bradford Island. Another study by Filice[10] found that changes in sediment quality can also affect species distribution, a finding also reported by Siegfried *et al*[11].

An early 1976 benthic study was one of the first to rigorously characterize the benthic environment of the upper Sacramento-San Joaquin estuary.[12] Seven stations were surveyed between Pittsburg and Decker Island, including three mid-channel stations at depths of about 9 meters, three near-shore stations at depths of 1 to 5 meters, and one station in the center of Sherman Lake at a depth of 1 meter. No significant vertical stratification or differences between stations were observed in pH, temperature, or dissolved oxygen. Water temperatures varied less than 5°C among the stations. Between May and October, salinity at Chipps Island varied less than 1 ppt, but salinity values were not reported for each survey.

Sediment analyses by Siegfried *et al* indicated a high degree of seasonal variability in sediment composition. In January 1976, following a year of relatively high outflow, sand was the primary substrate throughout the area. As outflow declined, finer material (silts and clays) began to accumulate. By late summer, fine material dominated the substrate at all stations except at Chipps Island. The strength of the current velocities at Chipps Island was thought to have prevented the deposition of fine sediments. The finer sediments began accumulating first in the lower reaches of the study area. The uppermost station, near Decker Island, was the last sandy substrate station to be covered by silt and clays. Sediment analyses also showed a strong positive correlation between the amounts of silts and clays and the concentrations of heavy metals, oil, and grease.

Much of the DWR benthic study area is surrounded by agricultural lands developed behind levees that channelize the natural water paths and control flooding of the farmlands. Over the course of time, some of the levees have failed, allowing the rivers to reclaim the land. Two of these areas are sampled in the DWR benthic monitoring program: Sherman Lake and Franks Tract. Industrial development in the study area is relatively sparse with the exception of the southern shore of Suisun Bay from the Antioch Bridge to the Benicia Bridge. Along this reach, industrial discharges from power plants, a paper processing plant, steel mills, and refineries enter the estuary in addition to discharges from the public wastewater treatment plants of the cities of Antioch, Pittsburg, Concord/Walnut Creek, and Martinez.

It is well known that the estuary is contaminated by domestic, industrial, and agricultural pollution.[13] An estuary-wide study completed in 1987 concluded that urban and industrial pollutant discharges were the greatest sources of sediment contamination.[14] However, while pollutant studies have found sediment contamination is widespread throughout the estuary, there is considerable variation and patchiness.[15,16] This variability and patchiness has prevented the development of an overall understanding of pollutant trends, and there are still many unknowns regarding the effects of sedimentary pollutants on estuarine biota.

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10 FP Filice. 1958. Invertebrates from the estuarine portion of San Francisco Bay and some factors influencing their distribution. *Wasmann Journal of Biology* 16:159-211.

11 CA Siegfried, AW Knight, ME Kopache. 1978. *Ecological Studies on the Western Sacramento-San Joaquin Delta During a Dry Year*. Dept Water Sci Eng Paper 4506. 121 pp.

12 Siegfried *et al*, 1978; cited.

13 A Davis, AJ Gunther, BJ Richardson, JM O'Connor, RB Spies, E Wyatt, E Larson, EC Meiorin. 1991. *Status and Trends Report on Pollutants in the San Francisco Estuary*.

14 Citizens for a Better Environment. 1987. *Toxic Hotspots in San Francisco Bay*. San Francisco. 193 pp.

15 Citizens for a Better Environment, 1987; cited.

16 E Long, D MacDonald, MB Matta, K VanNess, M Buchman, H Harris. 1988. *Status and Trends in Concentrations of Contaminants and Measures of Biological Stress in San Francisco Bay*. NOAA Technical Memorandum NOS OMA 41. National Oceanic and Atmospheric Administration, Seattle.

In summaries of available monitoring data, Gunther *et al*[17,18] concluded that the majority of pollutants entering the estuary came from river-derived inputs of urban and nonurban runoff. Researchers have tested a variety of inputs as well as the instream toxicity of the Sacramento and San Joaquin rivers over a wide geographic area. Results of USEPA-approved bioassays found that both rivers do contain acutely toxic water at certain times.[19,20] Both Connor and Foe found that sources and types of constituents thought responsible for instream contamination varied seasonally and from year to year but were generally tied to agricultural runoff into both rivers. The effects of these contaminants on the resident estuarine environment and its ecosystems are still a subject of investigation and discussion.

It is now known that phytoplankton biomass, as well as the abundance of many species of zooplankton and fish, significantly declined between 1970 and 1990.[21] Yet few cause-and-effect relationships linking changes in abundance at one level of the food chain to changes in another level have been established. Some research, however, has been completed on trophic relationships between the estuary's phytoplankton and benthos. In general, this work concludes that historical increases in benthic grazing pressure can, at times, substantially reduce the standing stock of phytoplankton over large but localized areas.[22,23] A recent and dramatic example of this relationship was documented after the introduction of the Asian clam, *Potamocorbula amurensis* into Suisun Bay (Figure 2). Thus, not only is the benthos dependent on phytoplankton as a food source, it may at times also regulate phytoplankton biomass. However, changes in the annual cycle of phytoplankton biomass levels may be more important to herbivores than the decline in total biomass. Annual blooms of phytoplankton are thought necessary to support annual increases in many herbivores.

Zooplankton are thought to comprise a minor portion of the total food supply for the benthos. The most important benefit to the benthos may be from the relatively small contributions that decomposed zooplankton make to the detrital carbon supply. Yet, the effect of the benthos on zooplankton densities may be more important than the contribution zooplankton make to the benthic food supply. *P. amurensis* has been shown to consume live zooplankton nauplii and may limit the abundance of some zooplankton populations.[24] The freshwater clam *Corbicula fluminea* probably also has the potential to consume zooplankton. These clams are two of the most abundant and widely distributed benthic species within the upper estuary.

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17 AJ Gunther, JA Davis, DJH Phillips. 1987. *An Assessment of the Loading of Toxic Contaminants to the San Francisco-Bay Delta.* Aquatic Habitat Institute, Richmond, CA. 330 pp.

18 AJ Gunther, JA Davis, DJH Phillips, KS Kramer, BJ Richardson, PB Williams. 1990. *Status and Trends Report on Dredging and Waterway Modification in the San Francisco Estuary.* San Francisco Estuary Project, Oakland, CA. 299 pp.

19 V Connor. 1988. "Survey Results of San Joaquin River Watershed Survey". Memo to J Bruns, California Regional Water Quality Control Board, Central Valley Region.

20 C Foe. 1988. "Results of the 1986-87 Lower Sacramento River Toxicity Survey" and "Preliminary 1988 Colusa Basin Drain Rice Season Biotoxicity Results". Memos to J Bruns, California Regional Water Quality Control Board, Central Valley Region.

21 For a review of trends in aquatic species, see B Herbold, AD Jassby, PB Moyle. 1992. *Status and Trend Report on Aquatic Resources in the San Francisco Estuary.* San Francisco Estuary Project. 257 pp. plus appendixes.

22 FH Nichols. 1985. Increased benthic grazing: an alternative explanation for low phytoplankton biomass in northern San Francisco Bay during the 1976-1977 drought. *Estuarine Coastal and Shelf Science* 21(3):379-388.

23 AE Alpine and JE Cloern. 1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. *Limno Oceanogr* 37:946-955.

24 WJ Kimmerer, BioSystems Analysis Inc, Tiburon, California; personal communication.

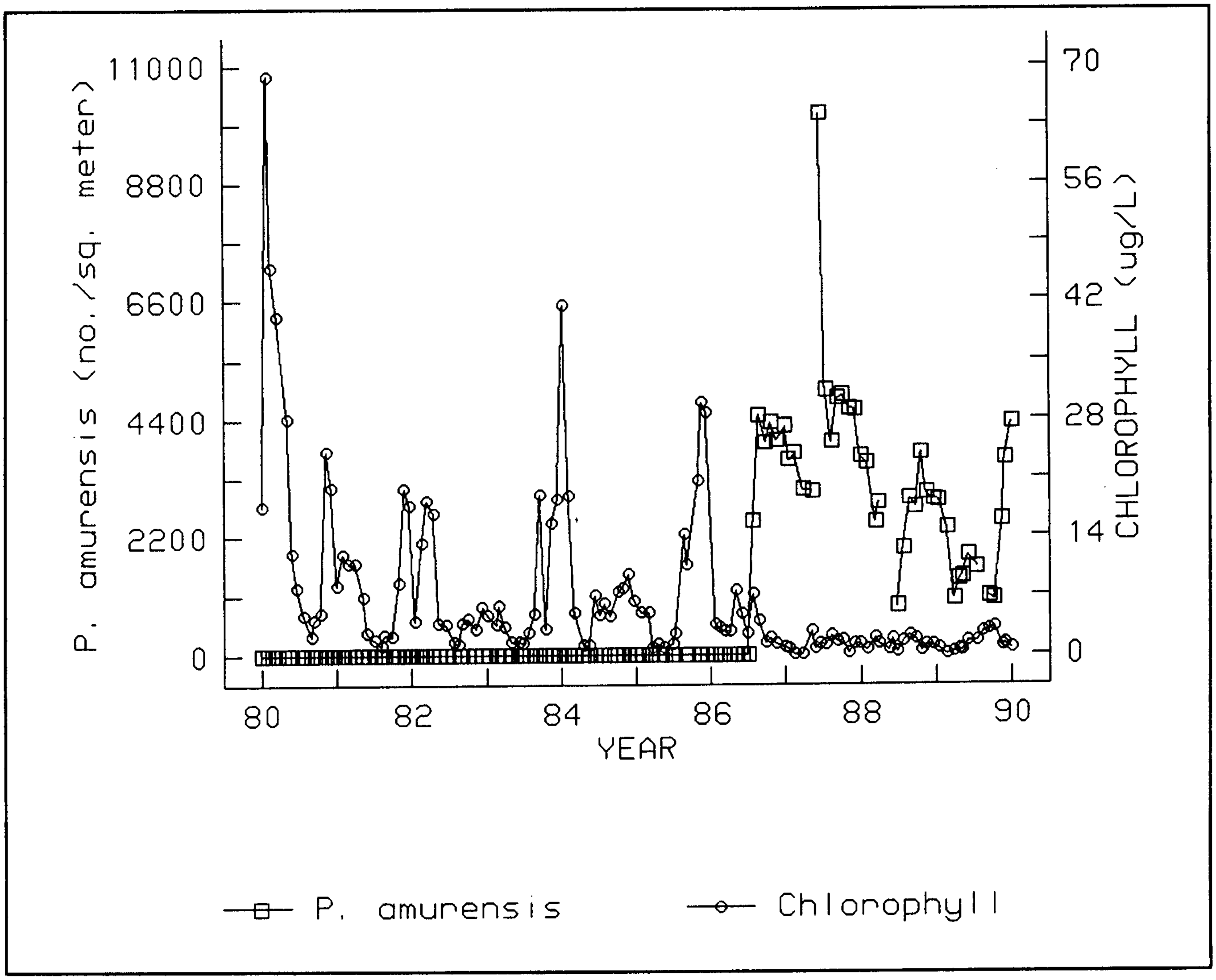

Figure 2
CONCENTRATIONS OF *P. AMURENSIS* AND CHLOROPHYLL *a* IN GRIZZLY BAY, SITE D7-C, 1980-1990

SURVEY AND ANALYSIS METHODS

The study area spans a variety of habitats from narrow, freshwater channels in the delta to broad, estuarine bays. The Sacramento-San Joaquin estuary is one of the largest estuaries in the United States. It is also one of the nation's most modified estuaries.[25] The many recorded changes have affected virtually every aspect of this estuary at one time or another. Changes such as urban development, wetland development, diversion of fresh water, alterations in sediment loadings, species introductions, and weather patterns all have the potential of affecting the benthos. Overall, the ecology of the estuary is primarily dictated by physicochemical processes; however, biological events such as introduction of exotic organisms have also had pronounced effects on the estuary's ecosystem.

The upper Sacramento-San Joaquin estuary is classified as a partially mixed and tidally dominated estuary. The estuary's hydrology is complicated by regional differences in geography, which strongly influence the system's hydrology. In general, tidal flows greatly exceed freshwater inflows except during periods of high streamflow in wet winters. A mixing zone of fresh water and salt water is always present, although its location is transient. Thus, salinity and water current patterns, which directly affect the distribution and transport of numerous organisms, vary according to local conditions throughout the study area.

Sediment loads and their distribution are additional features of the estuary that can affect the benthos. Water storage and diversion from major tributaries of the estuary have reduced the seasonal magnitude of freshwater inflows and the supply of sediment. Water velocities, bathymetry, and wind and weather patterns also affect sediment resuspension and composition at a given location. Both Suisun and San Pablo bays have extensive shoals. Sediments in these areas are often resuspended as a result of the winds common to the region and then transported by prevailing water currents.

During the monitoring period discussed in this report (1980–1990), monthly benthic samples were collected consistently from five stations in the upper estuary (Figure 1). These stations were chosen for more intensive sampling from a larger set of stations sampled biannually between 1975 and 1979. The five stations chosen were thought to represent major aquatic environments within the upper estuary.[26] Key characteristics and the criteria used to select each station are shown in Table 4 (page 5).

Benthic Organisms

The benthos of the delta and western bays includes a diverse assemblage of organisms that range from single-cell bacteria and ciliates to large crabs and clams. Changes in the benthic macrofauna (those organisms larger than 0.5 mm[27]) were documented in this monitoring program. For sampling purposes, each station was divided into a maximum of three sectors: right bank (R), left bank (L), and center (C). Thus, a sampling site is identified by the station and sector designations.

All samples were collected using a hydraulic winch and Ponar dredge. The dredge was fitted with screens that allow water to pass through on descent to minimize a bow wave effect on epifauna prior to impact. The Ponar dredge samples a bottom area of about 0.053 m^2 to a depth that varies with the type of sediment and the ability of the dredge to penetrate it. The number of organisms per square meter was determined by multiplying the count of organisms collected in each sample by 19 (*ie,* 1.0 m^2/ 0.053 $m^2 \cong 19$). Three replicate grab samples were collected from eight sites each month (Table 5).

25 FH Nichols, JE Cloern, SN Luoma, DH Peterson. 1986. The modification of an estuary. *Science* 231:525-628.

26 Markmann, 1986; cited.

27 Nichols and Pamatmat, 1988;cited.

Table 5
BENTHIC AND SUBSTRATE
SAMPLING STATIONS AND SITES

Station	Site*	Type of Sample**	Habitat
D4	R	Substrate/Benthos	River Channel
	C	Substrate/Benthos	
	L	Substrate/Benthos	
D7	R	Substrate	Shallow Bay
	C	Substrate/Benthos	
D11	R	Substrate	Flooded Tract
	C	Substrate/Benthos	
	L	Substrate	
D19	R	Substrate	Flooded Tract
	C	Substrate/Benthos	
	L	Substrate	
D28A	R	Substrate/Benthos	River Channel
	L	Substrate/Benthos	

* Sites are determined while facing downstream (Right, Center, Left).
** Substrate samples consist of one random grab.
Benthic samples consist of three grabs.

After collection, each sample was rinsed through a screen with 0.6-mm openings. All material remaining after washing was preserved with 25% formalin for laboratory analysis.

Laboratory analysis of the preserved samples consisted of sorting, identifying, and enumerating all whole organisms. Identifications were made to the lowest taxonomic level possible, usually species. A taxonomic list of all organisms identified from the monitoring samples (Appendix A) was continuously maintained. Scientific names are updated annually, as new organisms are identified or existing organisms are reclassified.

Hydrozoology, a private laboratory under contract with the State of California, analyzed all benthic samples. All organisms collected are preserved in ethyl alcohol and archived after identification and enumeration. Identification and enumeration data are entered into an electronic data base maintained by DWR as an SAS data set.

One of the goals in analyzing the benthic monitoring data was to arrange the monitored variables, represented by the sampling sites and collected species, in an ecologically meaningful order. The distribution of most species in a community is presumed to reflect the influence and variation of major environmental factors. Although such factors, and the species reflecting them, may not display a simple, continuous trend from one extreme to the other, the actual range of conditions in time or space can be viewed as a gradient. Environmental mosaics and interspecific relationships can make the interpretation of data from a community complex. Ordination techniques are recognized as methods that permit identification of major factors controlling the distribution of species[28]. The benthic monitoring data were analyzed using the ordination method of correspondence analysis available in the SAS package.

Correspondence analysis and its application are described in detail by Greenacre[29]. CA is a preferred method of ordination because the data transformation does not assume a linear relationship among the variables, which rarely occurs in ecological data. Also, there is a direct relationship between the species and sampling site scores because CA scales both the rows (species) and columns (sites) of the data matrix in the same manner. This second characteristic of CA allows the plotting and interpretation of both species and sampling site scores on the same axes. The CA scores from an individual axis can also be treated as normal random variates, as the scores on each axis are independent of one another. For this reason, CA scores can be used in further statistical tests to examine relationships between environmental variables and the benthic community. In this report, the CA sites scores were used in simple linear regression analyses to test for significant relationships between the CA scores and a variety of biotic and abiotic environmental variables measured at the benthic monitoring stations.

Sediment

Sediment composition was also measured as part of the benthic monitoring program. A single sediment sample was collected each month from 13 sites (Table 5). General trends in sediment composition are described for all sites where sediment samples were collected. Trends are depicted as the mean annual percentage of fines (silt and clay) and the mean annual percentage of organic material through time.

28 JJ Gonor and PF Kemp. 1984. *Procedures for Quantitative Ecological Assessments in Intertidal Environments.* US Environmental Protection Agency. Corvallis, OR.
29 MJ Greenacre. 1984. *Theory and Applications of Correspondence Analysis.* Academic Press. London.

For this report, however, the relationship between sediment composition and benthic species composition was investigated using data only from those eight locations where both benthic biota and sediment samples were collected.

Sediment samples were collected with the same winch and Ponar dredge set-up used in the infaunal sampling. A 1-liter subsample of sediment was haphazardly selected from a single dredge sample and stored. All sediment samples were analyzed at the DWR Soils Laboratory. Routine analysis of the sediment sample included determining the percent size fractions with the use of a mechanical sieve and hydrometer. Using the size fractionation data, the sample was categorized (on a percentage basis) as fines (silt and clay particles less than or equal to 0.08 mm in diameter), sand (particles greater than 0.08 mm in diameter), or gravel (particles greater than 2.5 mm in diameter). (During 1980 through 1990, no gravel was detected at any of the routinely monitored sites.) The percent organic content of each sediment sample was also routinely determined from the loss in weight of an oven-dried sample burned at 404°C for 8 hours. All laboratory analysis procedures follow the American Society for Testing Methods[30]. Data analyses included sediment data collected from 1981 through 1990, which were stored in a personal computer data base. Data for 1980 were not available.

Water Quality

DWR collects water quality data at 26 stations throughout the upper estuary (Figure 1) as part of the environmental monitoring stipulated in Decisions 1379 and 1485, which started in 1975 and continues to the present. Stations are generally sampled monthly between November and February and bimonthly the rest of the year. All samples are collected from a depth of 1 meter by submersible pump or Van Dorn water sampler at or near high slack tide. Field measurements included water temperature, specific conductance, pH, dissolved oxygen, turbidity, and Secchi disc depth. All other analyses were completed at the DWR Chemistry Laboratory using standard analytical methods.[31] Data are stored on the Environmental Protection Agency's STORET system.

For this report, trends in surface water temperature, specific conductance, and volatile suspended solids were characterized for three regions of the upper estuary (Figure 4). Specific conductance measurements were converted to salinity values using the formula:

Salinity (parts per thousand) $= -100(\ln(1-EC/178.5))$

Where: EC = specific conductance, in milliSiemens per centimeter.

Water temperature and specific conductance were measured on-site using electronic sensing equipment. The concentration of volatile suspended solids was determined from the loss in weight of an oven-dried total suspended solids sample burned at 550°C for 24 hours.[32] For all variables, annual means and 95% confidence intervals were calculated on a regional basis by pooling monthly data from all stations in a region and then averaging them over the calendar year.

Phytoplankton

DWR routinely sampled the composition and biomass of phytoplankton at numerous locations in the upper estuary as part of its environmental monitoring program. Taxonomic composition was assessed through microscopic analysis of water samples. Biomass measurements, used primarily to document the occurrence of abrupt increases in phytoplankton concentration (phytoplankton blooms), were estimated from measurements of chlorophyll *a* concentration of water samples routinely collected from 26 stations in the upper estuary (Figure 1). Changes in phytoplankton composition and biomass are summarized here using data from 16 stations and three regions (Figure 3).

Trends in chlorophyll *a* concentration anomalies were used to determine if total phytoplankton biomass changed over time. In this analysis, an anomaly value represents the mean annual concentration

30 American Society for Testing Materials. 1992. Annual book of ASTM standards, Section Four, Volume 4.08. *Soil, Rock Building Stones, and Geotextiles*. American Society for Testing Materials, Philadelphia.

31 LS Clesceri, AE Greenberg, RR Trussell (editors). 1989. *Standard Methods for the Examination of Water and Wastewater*. 17th edition. American Public Health Association, Washington, DC.

32 Clesceri *et al*, 1989; cited.

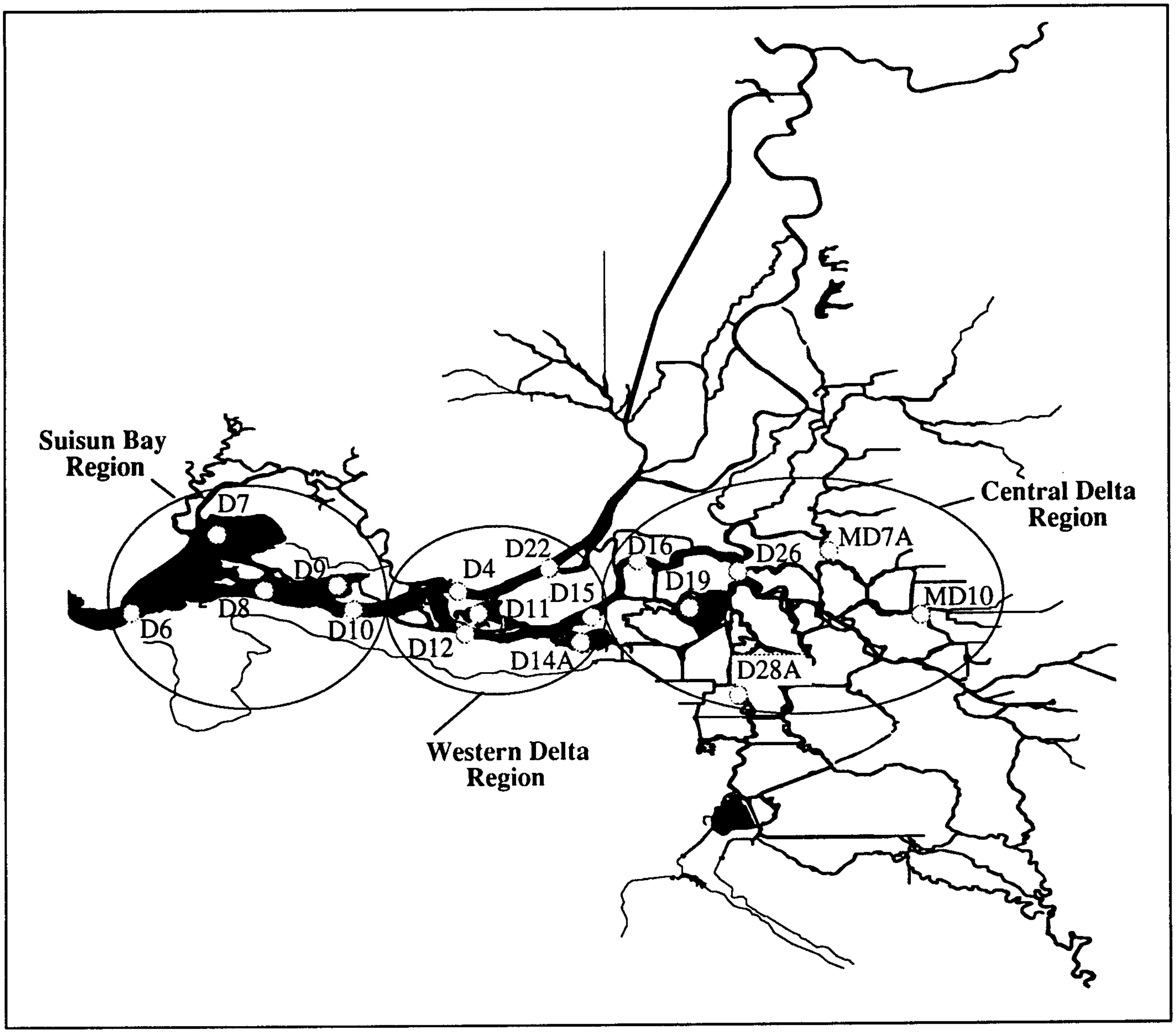

Figure 3
STATIONS AND REGIONS USED IN WATER QUALITY AND PHYTOPLANKTON ANALYSES

after subtraction of the long-term average. This transformation tends to dampen the influence of short-term changes such as those due to season or salinity. Anomalies greater than zero indicate the annual mean concentration was greater than the long-term average; anomalies less than zero indicate the annual mean concentration was less than the long-term average. More information on calculation of anomalies and a discussion of long-term trends in chlorophyll *a* for this estuary are available in Kimmerer's 1992 report[33].

To summarize anomaly data, annual mean anomaly values and 95 percent confidence intervals were calculated from a core data set after pooling data from stations within three geographically defined regions (Figure 3). Results are only presented for the regions from which benthic samples were collected, and only for 1978 through 1990. Linear regressions of trends in chlorophyll *a* anomalies were tested to determine if the slope of a regression line differed significantly from zero; non-linear relationships were not tested.

33 WJ Kimmerer. 1992. *An Evaluation of Existing Data in the Entrapment Zone of the San Francisco Estuary*. Interagency Ecological Studies Program, Technical Report 33. Department of Water Resources.

Zooplankton

Zooplankton abundance and distribution were monitored by the Department of Fish and Game. Zooplankton were sampled from a boat by towing a collection net from bottom to surface in a step-wise oblique 10-minute tow. Sampling surveys were conducted once in March, once in November, and twice each month in April through October. Laboratory analyses included sorting, identification, and enumeration of all samples.

Data are presently stored as SAS data sets. Methods for the zooplankton field sampling and laboratory analyses are described in more detail by Obrebski and others[34].

34 S Obrebski, JJ Orsi, W Kimmerer. 1992. *Long-Term Trends in Zooplankton Distribution and Abundance in the Sacramento-San Joaquin Estuary.* Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary, Technical Report 32. Department of Water Resources.

Chapter 3

TRENDS IN FACTORS INFLUENCING THE BENTHOS

In their community profile of the soft-bottom benthos of San Francisco Bay, Nichols and Pamatmat[35] concluded that many of the most dramatic interannual community changes may be attributable to extreme deviations in the physicochemical environment. These deviations may influence both the timing and success of recruitment and the survival of existing individuals. In this chapter we describe the trends in various physicochemical and biological variables that may affect the benthos of the upper estuary.

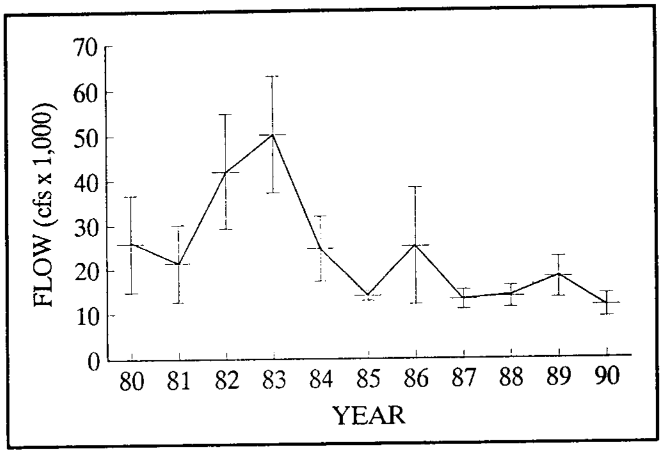

Figure 4
MEAN ANNUAL FLOW,
SACRAMENTO RIVER AT SACRAMENTO
Annual Means +/- 95% C.I.

Freshwater Flow

Freshwater flow strongly affects the physicochemical environment of the upper estuary. In addition to the direct effects on sediment composition and stability, freshwater flows affect salinity, water clarity, water temperature, and several other water quality variables. About 40% of California's watershed drains into the Sacramento-San Joaquin estuary, with the largest segment of this fresh water (about 72%) entering from the Sacramento River.[36]

From 1980 through 1990, the amount of fresh water entering the estuary has ranged over wide extremes, as indicated by mean annual Sacramento River flows at Sacramento (Figure 4). During this period, mean annual flows to the estuary were highest in 1983. They generally declined through 1985 and then increased sharply in 1986 because of extremely heavy precipitation during February. Freshwater flows have been persistently low since 1987, as a result of one of the most severe droughts in recent history.

The variability in freshwater flows within a year may be as important to the composition, abundance, and distribution of the benthos as the annual amount of freshwater entering the system. As indicated by Sacramento River flows, the monthly variability generally increases with the annual average. Thus, the low freshwater flows that prevailed between 1987 and 1990 were accompanied by reduced intra-annual variability. This variability, which is strongly related to seasonal changes, may be important in determining the recruitment success and distribution of benthic organisms with planktonic life stages.

Water Quality

Although many water quality variables are measured throughout the upper estuary, only a few could have directly affected benthic species composition and abundance. Many of the variables, such as nutrient concentrations or total dissolved solids, have little direct effect on the benthos over the range of values measured in this estuary. Other water quality variables, such as temperature, have been very stable over the years (Figure 5) and show little

35 FH Nichols and MM Pamatmat. 1988. *The Ecology of the Soft-Bottom Benthos of San Francisco Bay: A Community Profile*. US Fish & Wildlife Service Biological Report 85(7.19). 73 pp.

36 Comprehensive Region Framework Study Committee. 1971. *Comprehensive Framework Study, California Region; Appendix V, Water Resources*. US Bureau of Reclamation. 339 pp. plus tables and maps.

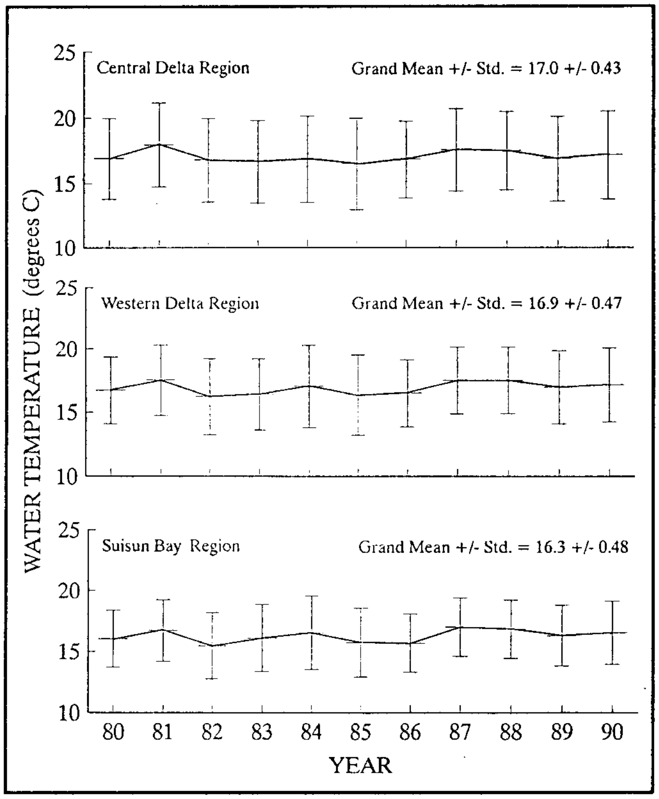

Figure 5
TRENDS IN WATER TEMPERATURE
Annual Means +/- 95% C.I.

connection to the variability in abundance and distribution of benthic organisms.

Freshwater inflow to the estuary is a principal determinant of the estuary's physical and chemical environment. The extreme fluctuations in freshwater flows observed between 1980 and 1990 produced similar, but inversely related, fluctuations in salinity levels. Salinity patterns are described on a regional basis because of the wide range in salinity between Suisun Bay and the central delta.

Fluctuations in salinity have been most extreme in the Suisun Bay region (Figure 6). Between 1980 and 1990, annual mean salinity in Suisun Bay ranged from 0.18 to 10.6 ppt. Salinity patterns in the western and central delta regions were similar to the pattern in the Suisun Bay region, but the range in values was smaller. In the western delta region, annual mean salinity ranged from 0.08 to 2.27 ppt (Figure 7). In the central delta region, annual mean salinity ranged from 0.06 to 0.25 ppt (Figure 8).

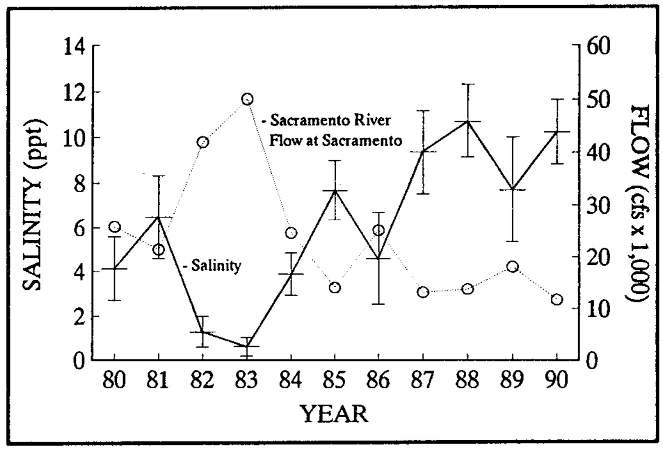

Figure 6
TREND IN ANNUAL SALINITY, SUISUN BAY REGION
Annual Means +/- 95% C.I.

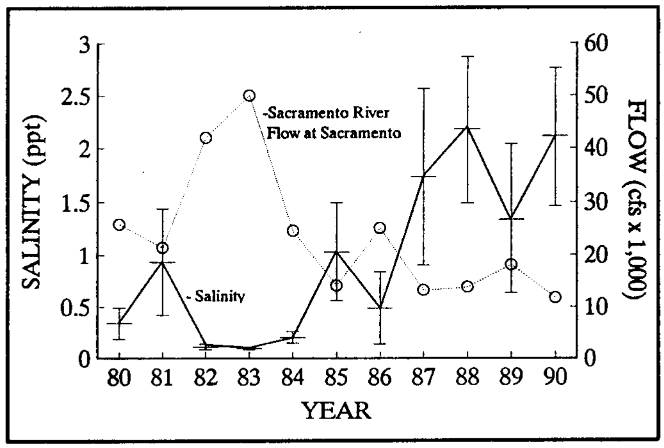

Figure 7
TREND IN ANNUAL SALINITY, WESTERN DELTA REGION
Annual Means +/- 95% C.I.

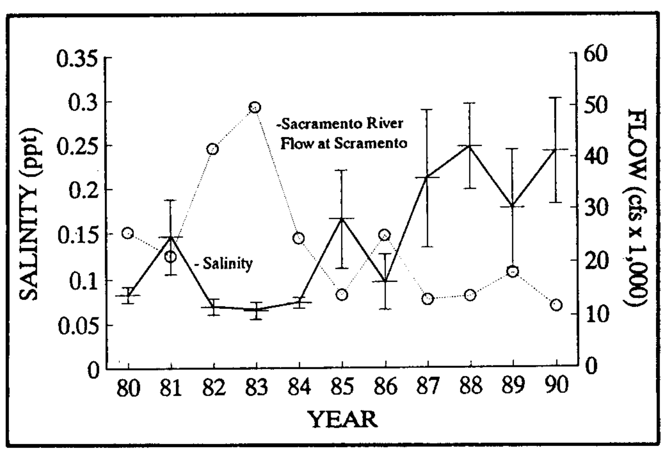

Figure 8
TREND IN ANNUAL SALINITY, CENTRAL DELTA REGION
Annual Means +/- 95% C.I.

Sediments

The substrate throughout the study area is entirely soft-bottom. The composition of the substrate is largely determined by the sediments present and the physical processes (wind and water motion) that move these materials. Changes in sediment composition can also occur as a result of bioturbation and biogeochemical processes, but in this estuary these effects are thought to be relatively minor compared to the physical processes. It is important to understand the trends in sediment composition, which can directly affect the benthos in terms of both the community composition and species abundance.

Both the inorganic and organic sediment fractions at sites D7-C and D7-R were extremely stable from 1981 to 1990 (Figure 9). The inorganic fraction was consistently dominated by fine material (silt and clay) and showed little variability. The organic fraction, which was mainly particulate organic matter, ranged from 7 to 10% at both sites.

The inorganic sediment fraction at Station D4 varied considerably at all sites (Figure 10). Sediment composition was most consistent in the center channel, where sand (% sand = 100 – % fines) was the dominant substrate type. From 1981 to 1990, the mean annual percentage of fines was consistently below 25%. The

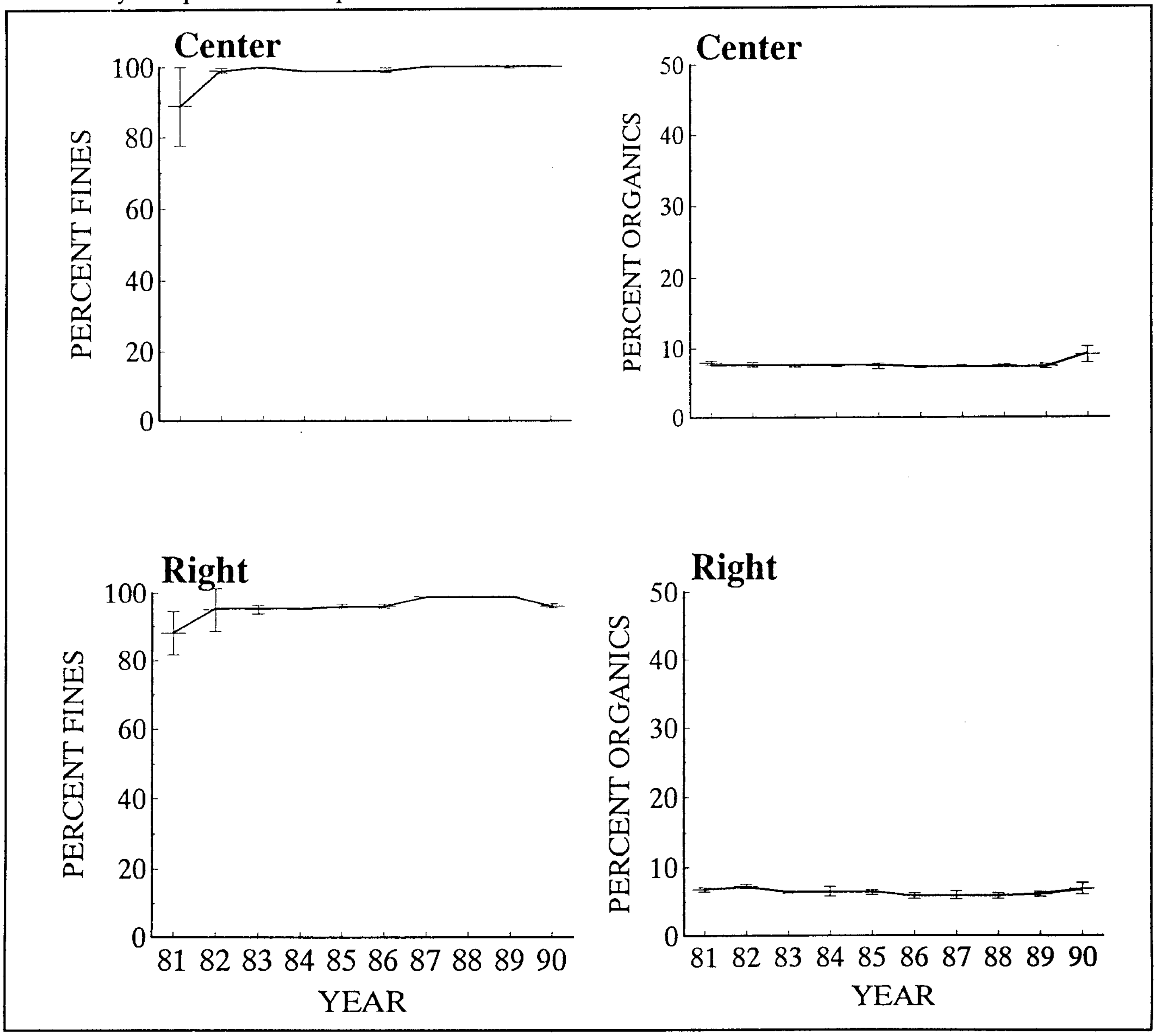

Figure 9
TREND IN ANNUAL PERCENTAGE OF FINE INORGANIC AND ORGANIC SEDIMENTS, GRIZZLY BAY, STATION D7

inorganic fraction was much more variable at D4-R. The mean annual percentage of fines ranged from 54% in 1984 to 94% in 1987 and was inversely related to Sacramento River flow (Figure 4). The percentage of fines at D4-R was generally higher after 1985, but declined sharply in 1990. Unlike D4-R, the mean annual percentage of fines at D4-L was not clearly related to Sacramento River flow. At the left bank, the mean annual percentage of fines ranged from 23% in 1987, to 61% in 1983.

The organic sediment fraction was much more stable than the inorganic fraction at station D4 (Figure 10). Organic content was lowest at D4-C, where the mean annual percentage ranged from 1 to 3%. The organic fraction was slightly higher at D4-R,

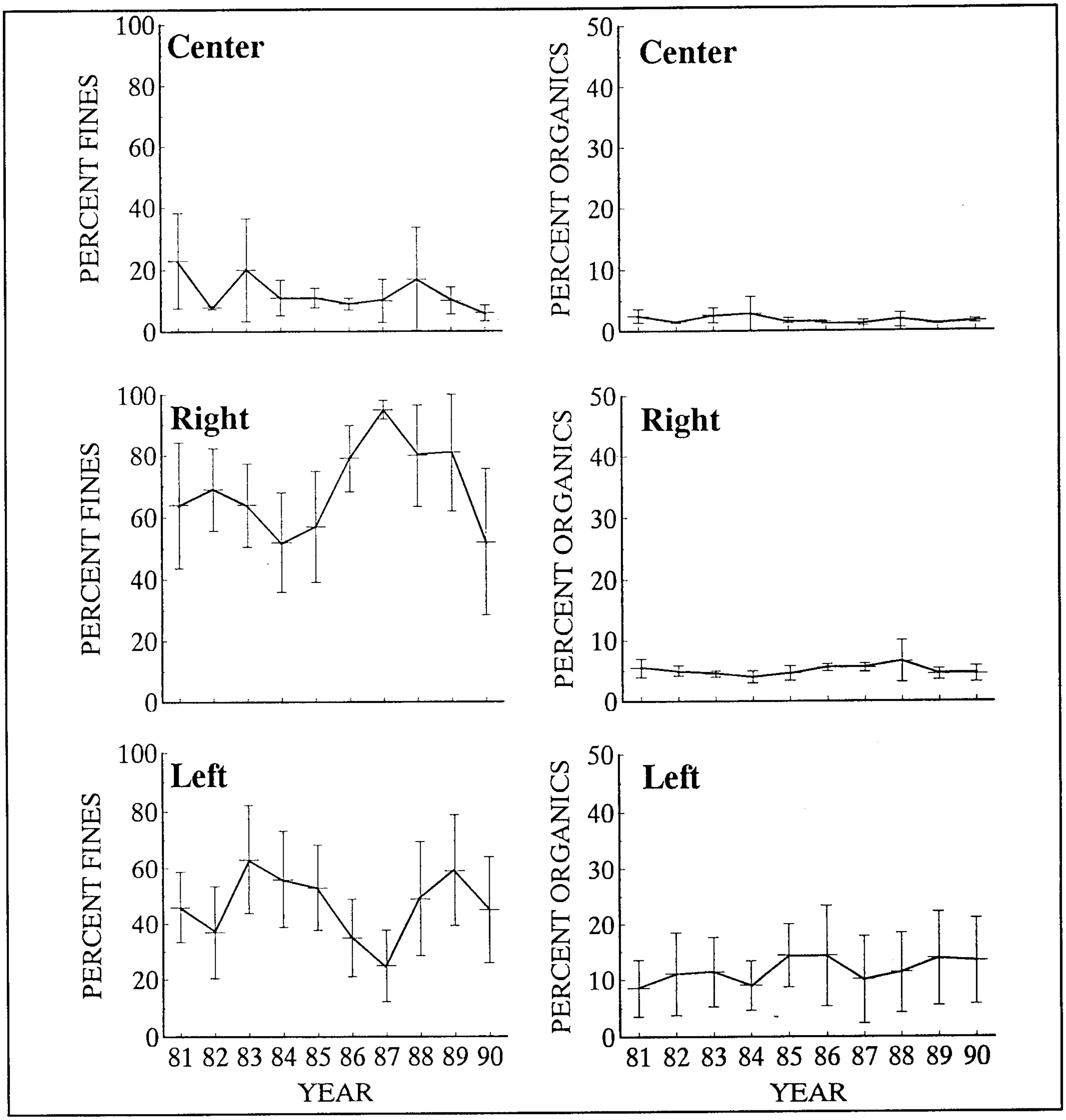

Figure 10
TREND IN ANNUAL PERCENTAGE OF FINE INORGANIC AND ORGANIC SEDIMENTS, SACRAMENTO RIVER, STATION D4

where mean annual percentages ranged from 4 to 6%. Organic content was highest but most variable at D4-L, where the mean annual percentage ranged from 8 to 13%.

The percentage of fines at Station D11 increased significantly ($P < 0.05$) at all sites from 1981 through 1990 (Figure 11). The inorganic fraction was most stable at D11-C, where mean annual percentage of fines ranged from 76 to 98%. The inorganic fraction varied most at D11-R, where mean annual percentage of fines ranged from 29 to 91%. By comparison, the percentage of fines was generally higher and less variable at D11-L, where mean annual percentage ranged from 37 to 93%.

The organic fraction at station D11 showed no significant trend over time at any of the sites (Figure 11). Organic content was generally lowest and most variable at D11-R (mean annual percentage 4-10%) and highest at D11-L (mean annual percent-

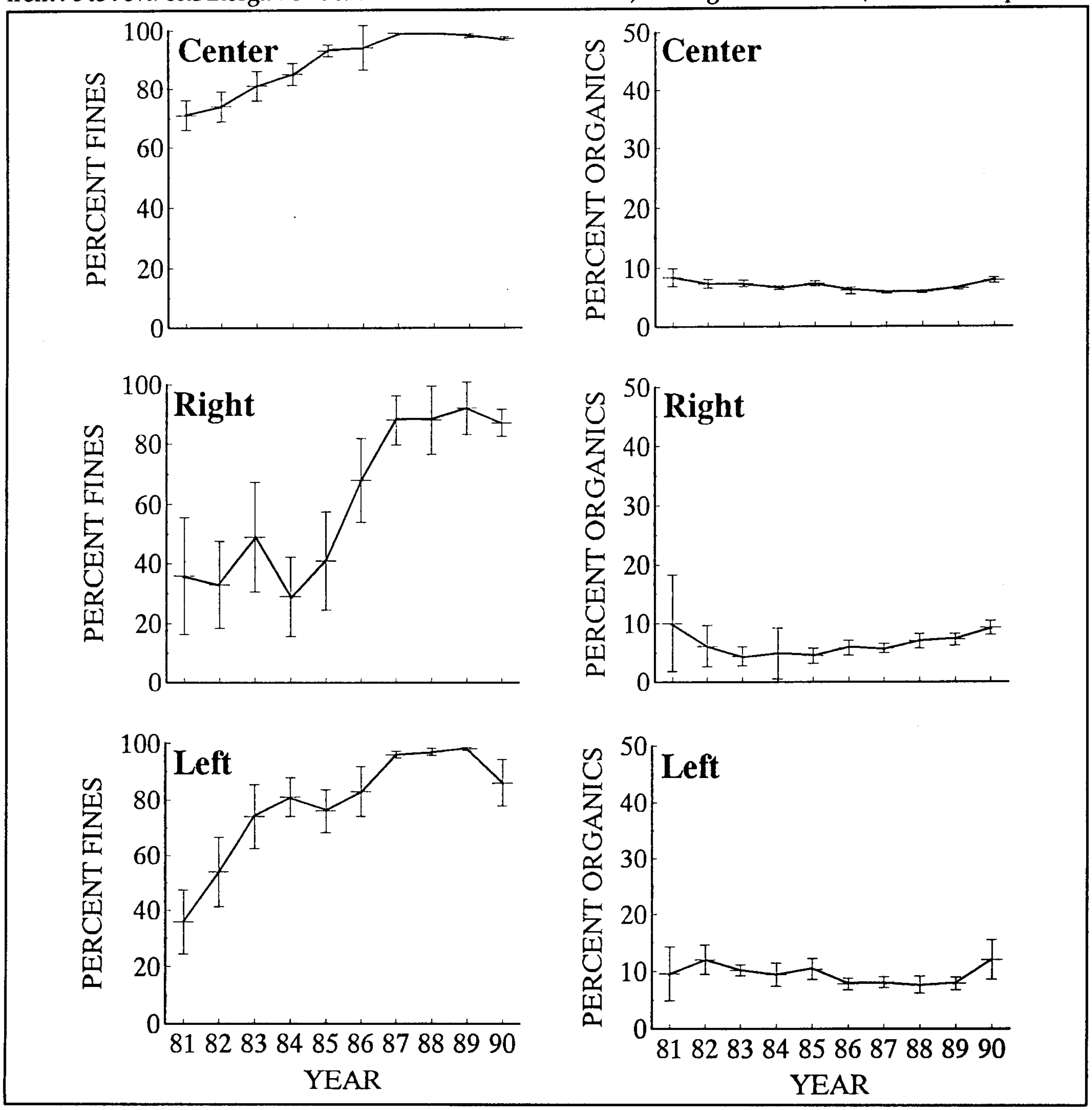

Figure 11
TREND IN ANNUAL PERCENTAGE OF FINE INORGANIC AND ORGANIC SEDIMENTS, SHERMAN LAKE, STATION D11

age 8-12%). Organic content was very stable at D11-C (mean annual percentage 7-8%).

Sediment composition clearly changed at station D19 from 1981 through 1990 (Figure 12). The percentage of fines increased at all sites sampled, and these increases were significant ($P < 0.05$) at D19-L and D19-R. The inorganic fraction was most stable at D19-C, where the mean annual percentage of fines ranged from 80 to 92%. At D19-R, the mean annual percentage of fines increased sharply between 1981 and 1982 (from 44 to 88%) and remained above 70% thereafter. At D19-L, the percentage of

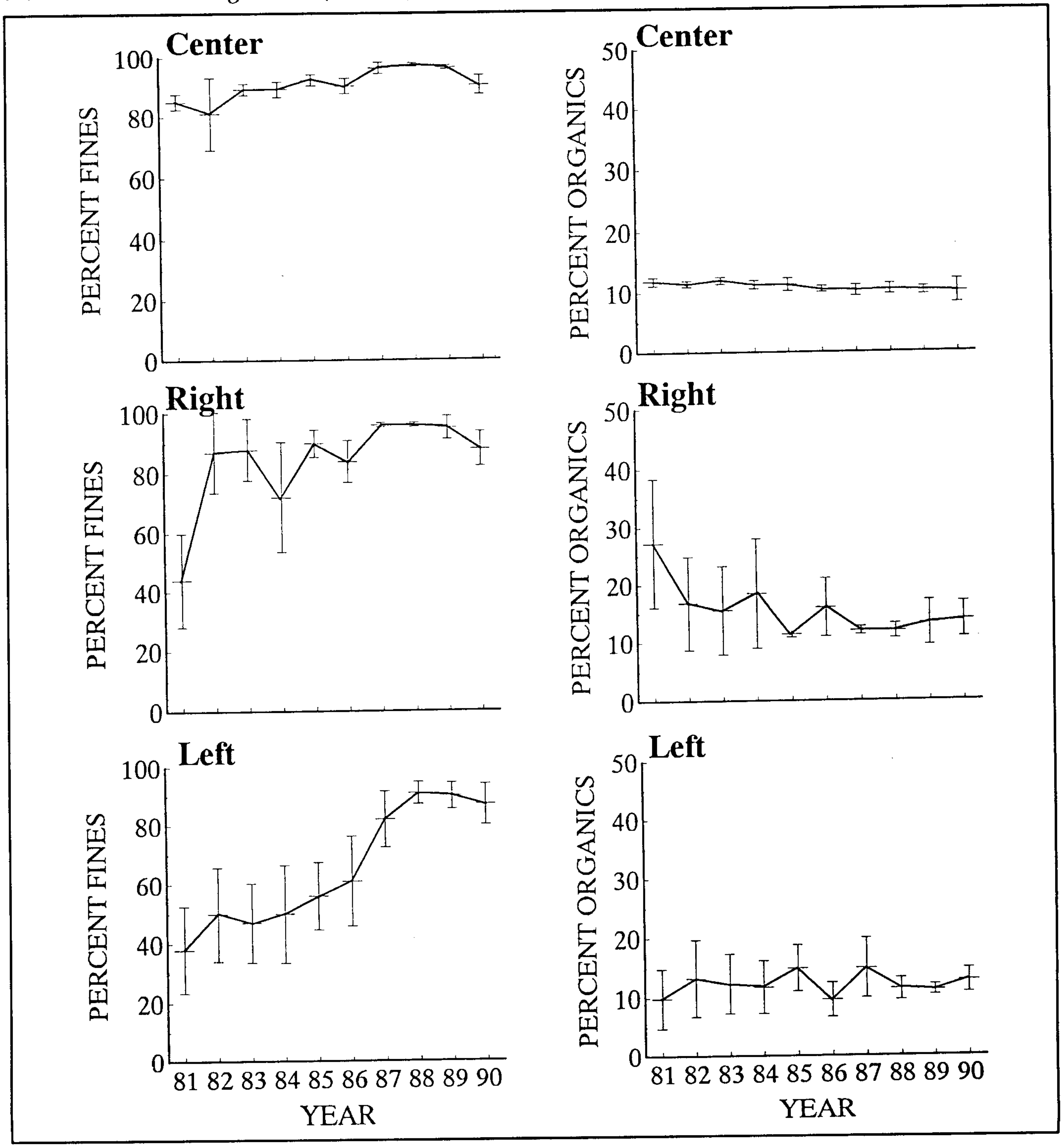

Figure 12

TREND IN ANNUAL PERCENTAGE OF FINE INORGANIC AND ORGANIC SEDIMENTS, FRANKS TRACT, STATION D19

fines showed a steady increase between 1981 and 1988, but declined slightly thereafter.

There was no significant trend in the organic fraction at D19 (Figure 12). Organic content was most stable at D19-C, where the mean annual percentage varied from 10 to 12%. Organic content was highest and most variable at D19-R, where the mean annual percentage ranged from 11 to 27%. Organic content at D19-L was relatively consistent compared to the significant increases in percentage of fines. Here the mean annual percentage of organic material ranged from 9 to 13%.

Patterns of inorganic content varied between the right and left banks of station D28A (Figure 13). The mean annual percentage of fines at D28A-R ranged from 70 to 95% and remained above 80% after 1986. At D28A-L, the mean annual percentage of fines ranged from 38 to 58% before 1986, and from 58 to 88% after 1986.

Organic content was much less variable at both D28A sites (Figure 13). The mean annual percentage of organics was somewhat higher at D28A-R, ranging from 8 to 12%. The mean annual percentage of organics ranged from 5 to 10% at D28A-L.

Overall, inorganic material was the dominant component of the sediment at all sampling locations. Fines predominated at the non-channel stations (D7, D11, D19), and the mean annual percentage of fines increased significantly over time at most locations. The inorganic fraction showed no clear trend

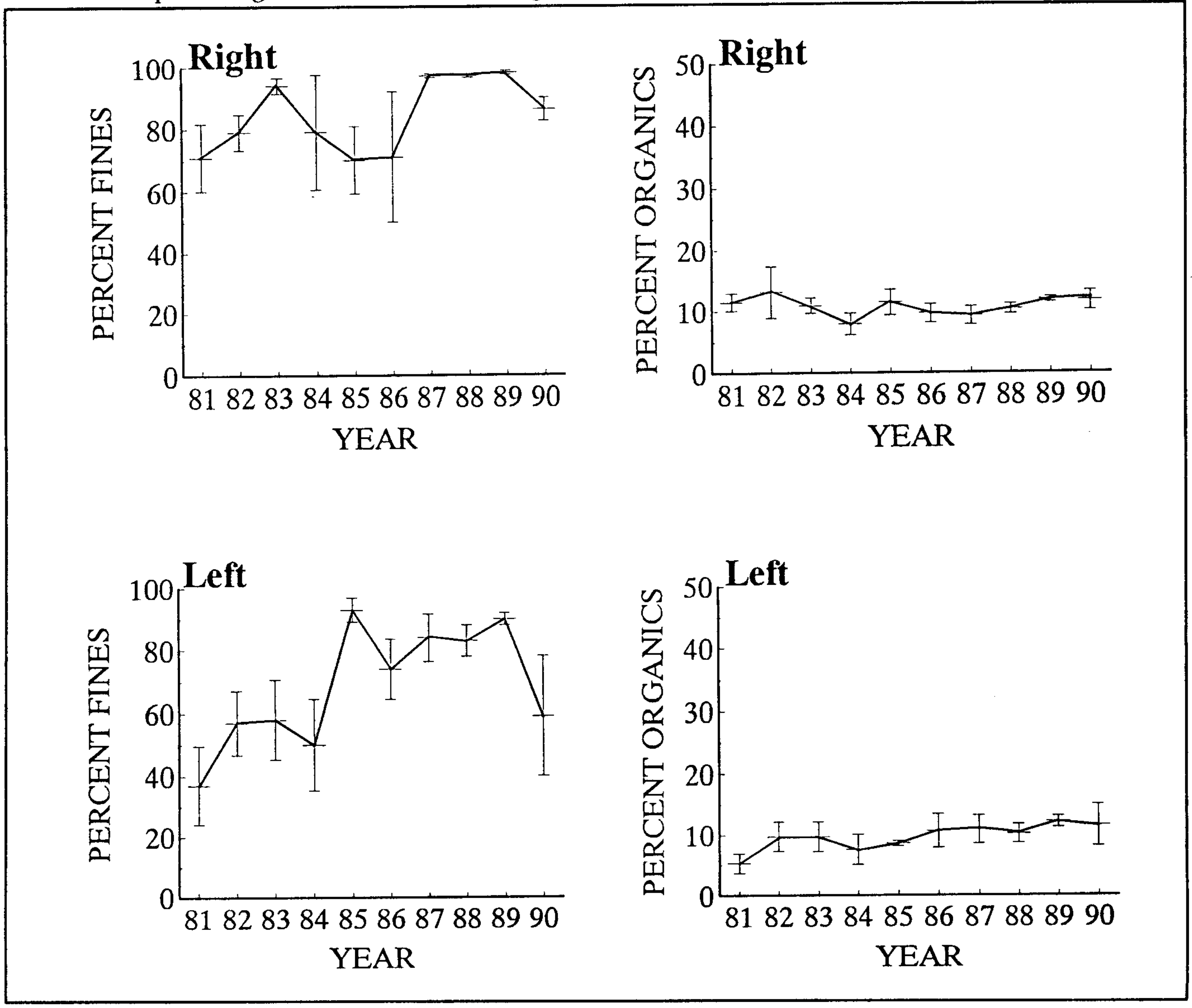

Figure 13
TREND IN ANNUAL PERCENTAGE OF FINE AND ORGANIC SEDIMENTS, OLD RIVER, STATION D28A

at the channel stations (D4, D28A), but many locations had increased amounts of fines during the drought (1987–1990). Organic content showed no significant trend through time at any station. Qualitative laboratory observations found peat to be the dominant organic material at all sites except at D7.

Food Supply

Abundance and distribution of benthic organisms can be affected by numerous biological, physical, and chemical processes. Food supply is a biological factor that affects growth rates, survivorship, and fecundity of benthic organisms. Thus, changes in food supply influence several life stages, leading to direct population effects.

The relationship between food supply and the abundance of a benthic organism may not be linear. If sufficient food is available to consumers, their abundance will not be affected by any further increase in food supply. However, food concentrations that remain chronically below the level required for growth and/or reproduction will have deleterious effects on the consumer's abundance. Determining the effects of changes in the quality and quantity of food, whether through inferences or specific studies, is difficult. Trends in food abundance and benthos abundance can be compared, using correlation analysis of monitoring data, to determine if relationships exist; however, the cause and effect of these relationships are inferred and cannot be proven by the analysis. The major use of the correlation test is to identify relationships that warrant further investigation.

In this section, trends in three potential food sources, volatile suspended solids, phytoplankton, and zooplankton, are described based on analyses of routine monitoring data. Volatile suspended solids (which include phytoplankton and other particulate organic matter) are thought to be primary food sources for many benthic invertebrates. Although zooplankton are a minor food source for some benthic organisms,[37] a description of their trends in relation to other food sources provides a more complete picture of possible secondary links between the lower food chain levels and the effects that zooplankton grazing on phytoplankton may have on the benthos. Other items, such as benthic microalgae and bacterioplankton that may also be important benthic food sources, were not measured during this study.

Volatile Suspended Solids

Volatile suspended solids are the organic portion of total suspended solids. This suspended organic material may represent a food source for both benthic and pelagic organisms, but studies to determine the importance of VSS to the benthic food supply have not been completed for this estuary.

Mean annual concentration of volatile suspended solids was generally highest in Suisun Bay and lowest in the central delta (Figures 14–16). In Suisun Bay, mean annual concentration ranged from 4.3 to 10.1 mg/L. The concentration decreased significantly ($P < 0.05$) between 1978 and 1983 but showed no significant trend thereafter. VSS levels in 1983 were about 40% lower than in 1978. In the western delta, mean annual concentration ranged from 3.2 to 6.7 mg/L. Concentrations were highest in the western delta during 1978, were lower but stable from 1979 through 1985, and then increased somewhat but remained variable thereafter. In the central delta, mean annual VSS concentration ranged from 2.4 to 4.7 mg/L from 1978 through 1990. The concentration declined between 1978 and 1979 but remained fairly stable thereafter. General trends among the three regions suggest the concentration of VSS declined early on over much of the study area. Although concentrations were relatively stable in both the central and western delta from 1980 through 1990, VSS concentration did decline in the Suisun Bay region.

37 W Kimmerer; personal communication.

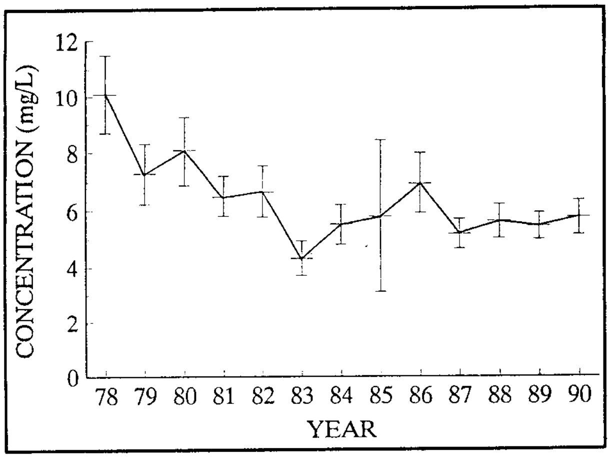

Figure 14
TREND IN VOLATILE SUSPENDED SOLIDS, SUISUN BAY REGION
Annual Means +/- 95% C.I.

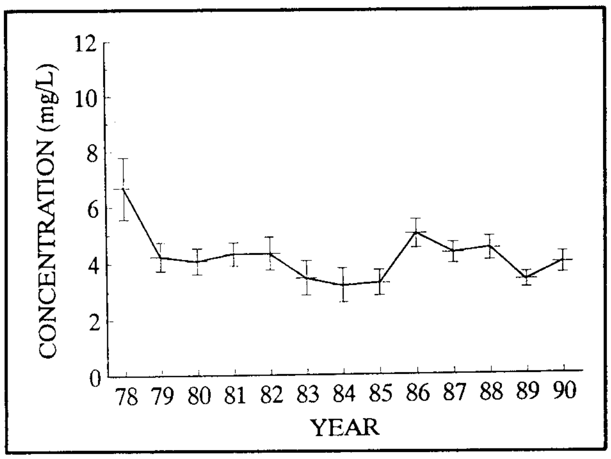

Figure 15
TREND IN VOLATILE SUSPENDED SOLIDS, WESTERN DELTA REGION
Annual Means +/- 95% C.I.

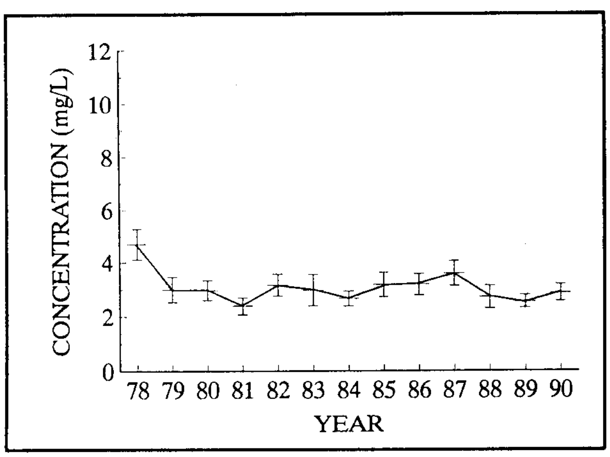

Figure 16
TREND IN VOLATILE SUSPENDED SOLIDS, CENTRAL DELTA REGION
Annual Means +/- 95% C.I.

Phytoplankton

Between 1978 and 1990, seasonal peaks in phytoplankton biomass (blooms) occurred in all regions of the upper estuary examined (Figure 17). Phytoplankton blooms typically occur between spring and fall and are most often dominated by one of four diatom genera: *Skeletonema* sp., *Thalassiosira* sp., *Cyclotella* sp., or *Melosira* sp. From 1980 through 1990, *Melosira* sp. was the dominant bloom organism in the delta, and *Thalassiosira* sp. dominated in Suisun Bay.

In the central delta region, mean annual chlorophyll *a* concentrations were moderate (4–12 μg/L) and variable between 1978 and 1990 (Figure 18). Annual anomalies of chlorophyll *a* concentration, which showed no statistically significant linear trend, were associated with relatively large confidence limits. In these cases, a high seasonal variability may be masking the lower variability in annual changes of phytoplankton biomass. Anomalies of chlorophyll *a* did exhibit a convex curve-shaped trend, with negative values between 1978 and 1981, positive values between 1982 and 1986, and negative values between 1987 and 1990.

The western delta is a convergence zone between the northern and central delta regions and Suisun Bay (Figure 4). As a result, physical, chemical, and biological processes in this region are often driven by events that originate in the surrounding areas. Annual variations in the mean chlorophyll *a* concentrations were generally moderate (4–12 μg/L) (Figure 18). Annual anomalies of chlorophyll *a* show phytoplankton biomass has declined significantly ($P < 0.05$) in this region, particularly during the last 4 years. Anomaly values increased between 1978 and 1982, declined sharply in 1983, increased through 1986, and declined steadily thereafter. The sharp decline in 1983 may reflect a downstream shift in the position of the entrapment zone and associated phytoplankton as a result of the extremely high outflows that occurred during winter and spring.

In the Suisun Bay region, mean annual chlorophyll *a* concentrations remained below 5 μg/L from 1978 through 1990 (Figure 18). Annual anomalies of chlorophyll *a* show a significant ($P < 0.05$) linear decrease in phytoplankton biomass over the last 13 years. The 1990 anomaly value was somewhat higher than the 1989 value; however, the average phytoplankton biomass generally remained at extremely low levels in this region.

Overall, phytoplankton biomass has declined significantly since 1986 throughout much of the upper estuary. In addition, a decrease in the frequency and intensity of phytoplankton blooms in many regions of the upper estuary has been noted since 1987.

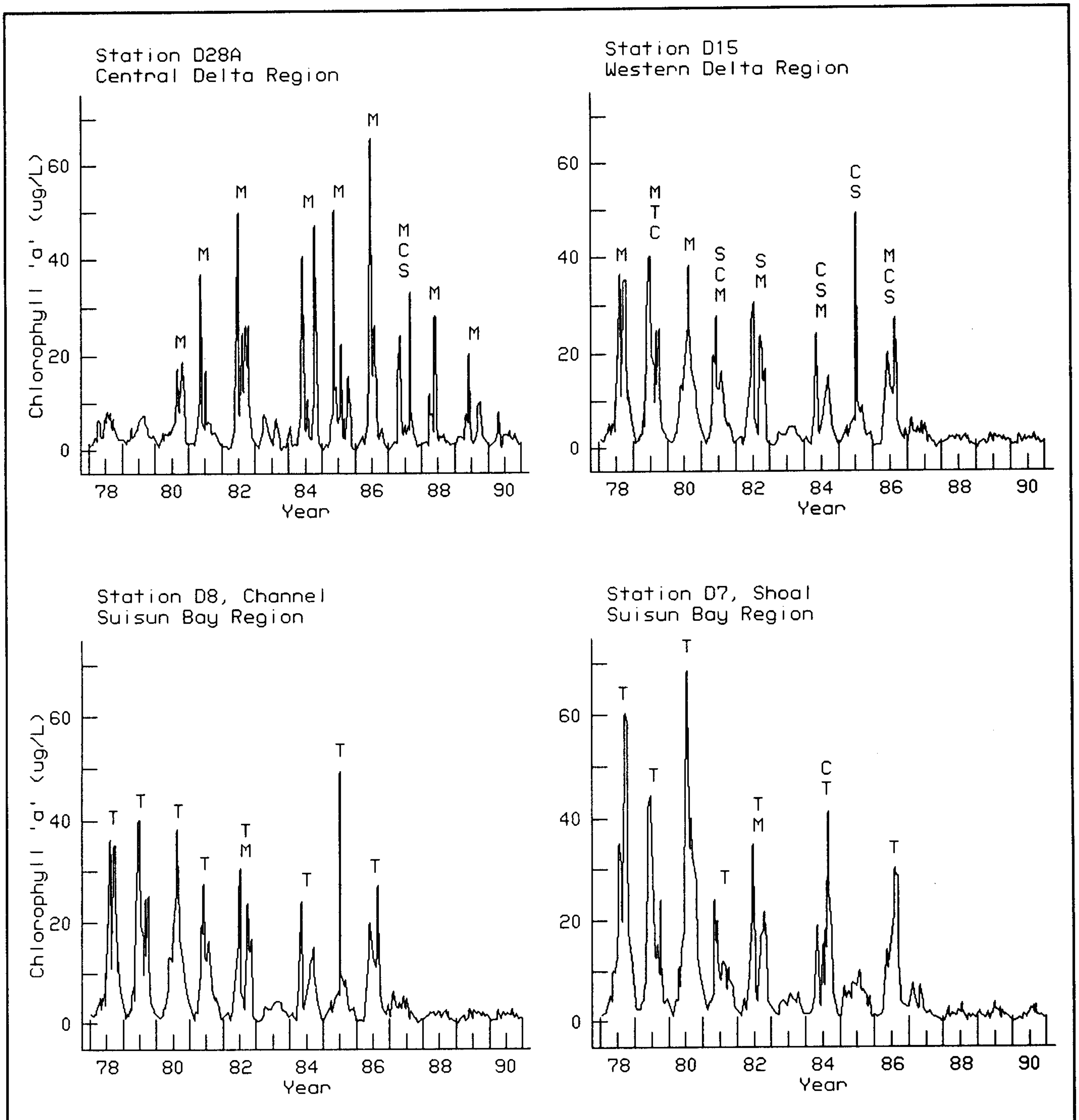

Figure 17

CHLOROPHYLL *a* CONCENTRATIONS AT VARIOUS STATIONS IN THE UPPER ESTUARY

Letters above peaks denote dominant bloom organisms:
C = *Cyclotella* sp., S = *Skeletonema* sp., T = *Thalassiosira* sp., M = *Melosira* sp.
Site locations are shown in Figure 1.

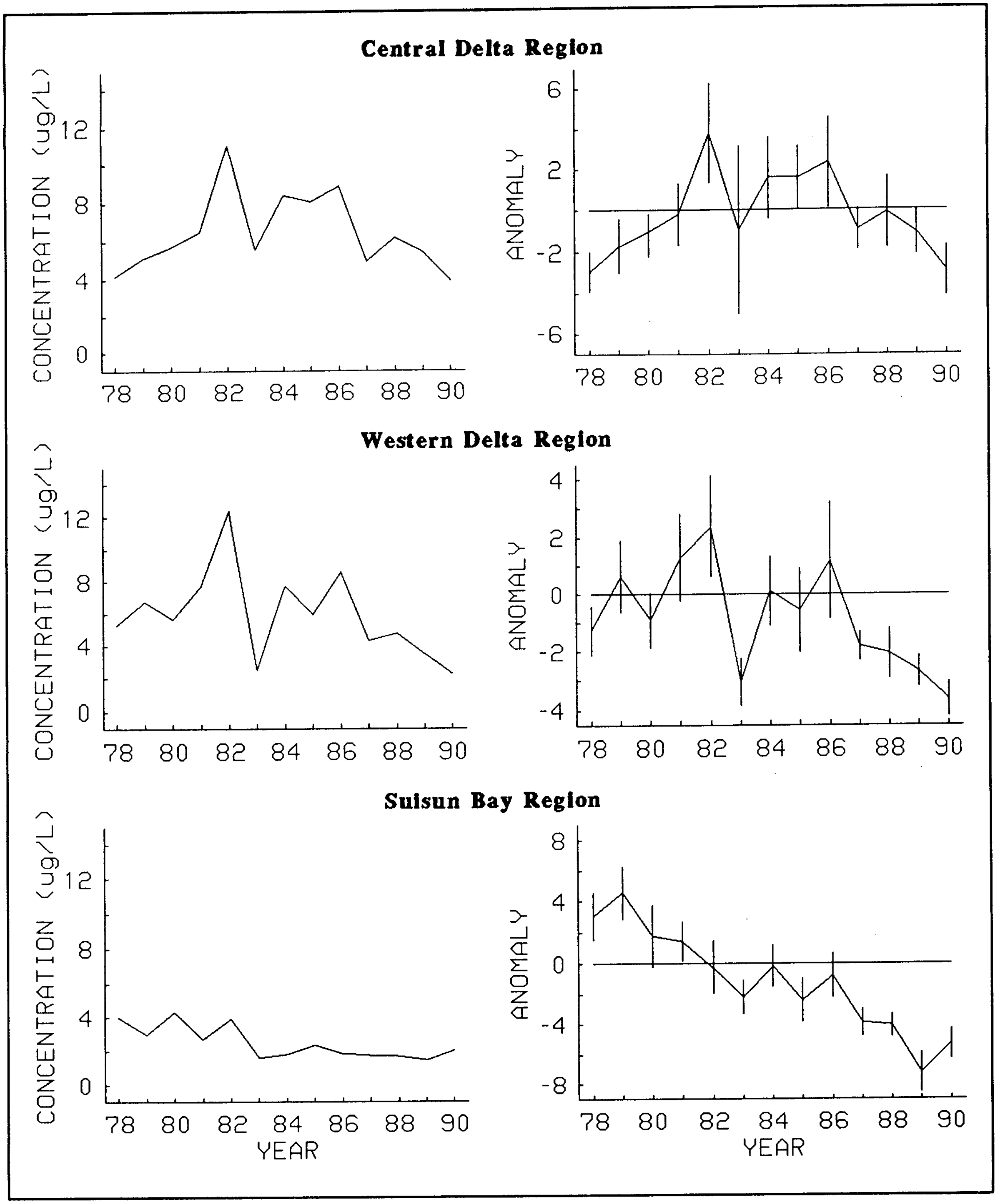

Figure 18
CHLOROPHYLL *a* CONCENTRATION AND ANOMALIES VERSUS TIME
Graphs on left are mean annual concentration, in µg/L.
Graphs on right are mean annual anomalies and 95% confidence intervals (vertical bars).

Zooplankton

Zooplankton occupy an intermediate level in many estuarine food chains, because most feed on primary carbon sources and because they are a major food source for various life stages of several estuarine fishes. In this estuary, salinity and season are the major factors related to between-year and within-year fluctuations in zooplankton stocks.[38]

The analysis of DFG zooplankton compliance monitoring data completed by Obrebski and others in 1992 used methods similar to those described above for the analysis of phytoplankton data to determine long-term trends in zooplankton abundance. Results show 12 of the 20 zooplankton taxa routinely sampled have undergone significant declines in abundance between 1972 and 1988. Seven taxa exhibited no abundance trend and one introduced copepod, *Oithona davisae*, increased in abundance (Table 6). Obrebski *et al* also examined regional and seasonal trends in zooplankton abundance. Results showed that declines in zooplankton abundance were scattered throughout the upper estuary but were more prevalent in the Sacramento and San Joaquin rivers than in Suisun Bay (Table 7). Zooplankton abundance trends exhibited no clear seasonal pattern (Tables 6 and 7).

Table 6
SUMMARY OF CHANGES IN SUISUN BAY/DELTA ZOOPLANKTON ANOMALIES
Results of Regression Analysis of Annual Mean Anomalies

	Pooled Data (All Months)	Spring (Mar-May)	Summer (Jun-Aug)	Fall (Sep-Nov)
COPEPODS				
Acartia	O	O	O	O
Diaptomus	D**	O	D**	D***
Eurytemora	D***	D**	D***	D**
Harpacticoics	D**	D**	D*	D*
Cyclopoids	D*	O	O	D*
Sinocalanus	O	O	O	O
Limnoithona	O	O	O	O
Oithona davisae	I*	O	I*	I*
CLADOCERA				
Bosmina	O	O	O	O
Daphnia	D*	O	D*	D*
Diaphanosoma	D*	U*	D*	D***
ROTIFERA				
Asplanchna	D**	D*	D**	D**
Keratella	D***	D**	D**	D***
Polyarthra	D***	D***	D***	D***
Synchaeta spp.	O	O	O	O
Synchaeta bicornis	D***	D**	D***	D***
Trichocerca	D***	D**	D**	D**
OTHER				
Neomysis	D*	O	O	D**
Barnacle Nauplii	O	O	O	O
Crab Zoea	O	O	O	O

O = No Change, D = Decline, I = Increase, U = U-Shaped Trend
* 0.01 <P <0.05
** 0.001 <P <0.01
***P <0.001

SOURCE: S. Obrebski, J.J. Orsi, W. Kimmerer. 1992. *Long-Term Trends in Zooplankton Distribution and Abundance in the Sacramento-San Joaquin Estuary.* Interagency Ecological Studies Program, Technical Report 32. Department of Water Resources.

38 Obrebski *et al*, 1992; cited.

Table 7

SUMMARY OF REGIONAL CHANGES IN ABUNDANCE OF ZOOPLANKTON TAXA THAT DECLINED BETWEEN 1972 AND 1987

Numbers are adjusted R^2 for either a linear or quadratic model, whichever yielded the highest R^2.
AL = Data pooled for all months, SP = Spring, SU = Summer, FA = Fall

	Suisun Bay				Sacramento River				Lower San Joaquin River				Western Delta				Entrapment Zone				Upper San Joaquin River			
	AL	SP	SU	FA	AL	SP	SU	FA	AL	SP	SU	FA	AL	SP	SU	FA	AL	SP	SU	FA	AL	SP	SU	FA
Diaptomus	.33*	NS	NS	.55**	.29*	NS	.24*	.36*	.23*	NS	NS	.41*	.62**	.25*	.57***	.60**	.52**	NS	.31*	.67***	.26*	NS	NS	.57**
Eurytemora	.26*	NS	.20*	.22*	.57**	.50**	.42*	NS	.67***	.50***	.44**	.61**	.40*	.36*	.42*	NS	.68***	NS	.52**	.63**	.39**	NS	.61***	.21**
Harpacticoids	NS	NS	NS	NS	.20*	NS	.29*	NS	.73***	.58***	.58**	.61**	NS	NS	.23*	NS	.57**	NS	NS	.59**	NS	NS	NS	NS
Cyclopoids	NS	NS	NS	NS	NS	NS	NS	NS	.22*	NS	NS	.23*	.40*	NS	.31*	.34*	.37*	NS	NS	NS	NS	NS	NS	NS
Daphnia	NS	NS	NS	NS	NS	NS	NS	NS	.32*	NS	.31*	.36*	.48*	NS	.38*	.42**	.59**	NS	.41*	.41**	NS	NS	NS	NS
Diaphanosoma	NS	NS	NS	NS	.72***	.60**	.63**	.41**	.78***	NS	.45*	.74***	.44**	NS	.35*	.64*	.37*	NS	NS	.60**	NS	NS	NS	NS
Neomysis	.45**	NS	.45*	.70***	.62**	.46**	NS	.62**	.39*	NS	NS	.57**	.65***	.62**	NS	.47**	.55**	.58**	NS	.57**	.36**	NS	.23*	.61**
Trichocerca	.61**	.54**	.59**	.58**	NS	NS	.29*	NS	.30*	.21*	.51**	NS	NS	NS	NS	NS	.58**	.46**	.52**	NS	.59**	.47**	.59**	.55**
Polyarthra	.69***	.74***	.47**	.64**	.87***	.58**	.86***	.69***	.93***	.72***	.91***	.73**	.89***	.73**	.86***	.88***	.93***	.78***	.87***	.80***	.73**	.73**	.64**	.70**
Synchaeta bicornis	.46**	.30*	.68***	.47**	.62***	.51**	.49**	.35*	.53**	.34*	.50**	.31*	.59***	NS	.49**	.34*	.58**	.38*	.54**	.54**	.50**	.30*	.45*	NS
Asplanchna	.39*	NS	NS	NS	.84***	.77***	.79***	.75***	.82***	.70***	.81***	.74***	.50**	NS	.59**	.46*	.76***	.62**	.72***	.60**	.53**	.38*	.23*	NS
Keratella	NS	NS	NS	NS	.89***	.74***	.83***	.75**	.90***	.60**	.87***	.71**	.78***	.57**	.74***	.85***	.91***	.74***	.70**	.88***	.77**	.64**	.51*	.71**

NS Not Significant
* 0.01 < P <0.05
** 0.001 < P<0.009
*** P<0.001

SOURCE: S. Obrebski, J.J. Orsi, W. Kimmerer. 1992. *Long-Term Trends in Zooplankton Distribution and Abundance in the Sacramento-San Joaquin Estuary.* Interagency Ecological Studies Program, Technical Report 32. Department of Water Resources.

CHANGES IN THE BENTHOS

The large number of benthic species identified through the monitoring program and the extreme variability in their abundance present a major challenge to efforts to detect long-term changes in the benthos and to identify probable causes for those changes. From 1980 through 1990, a total of 196 species were identified from all stations. On the average, 12 species were identified at any one location each month. The majority of these organisms generally occurred in low (<100 individuals/m^2) abundance or were found only sporadically. Typically, the four numerically dominant organisms at each location accounted for at least 80% of the total abundance at any one time.

There was also substantial temporal variability within the benthos of the upper estuary. It was not uncommon for monthly abundance to vary by an order of magnitude. An examination of the graphs in Appendix B gives some indication of the temporal variability in community abundance. Also, the graphs of the mean monthly abundance of the four numerically dominant organisms illustrate the temporal and spatial variability of individual species.

Correspondence analysis (CA) was used to investigate long-term changes in benthic species abundance and persistence, given the large number of species collected and the temporal and spatial variability common in the benthos. (CA methods are described in more detail in Chapter 2.) It is important to remember, however, that results for each site are relative responses to changes in benthic species abundance and persistence based on the suite of sites compared. Thus, the choice of sites compared directly affects the results.

Data from all sites were analyzed initially to determine if any differences among sampling sites existed. Annual mean abundances of the species were used to reduce seasonal variation within the data set, which could obscure long-term patterns of species abundance differences among sampling sites. CA results from the first CA dimension, which explains 33.7% of the total variation in the data set, show several distinct responses among the sites (Figure 19). Between 1980 and 1984, benthic species abundance and persistence was remarkably stable, with little deviation among sites or years. Beginning in 1985, however, the patterns of response among sites diverged. Site D7-C (Grizzly Bay) showed the largest response; followed by the three Sacramento River sites (D4-R, D4-L, D4-C), which showed an intermediate response. The remaining upper estuary sites (D11-C, D19-C, D28A-L, D28A-R) showed little response, which suggests little change in benthic species abundance and persistence during the sampling period. Using these response patterns, sites were grouped as: Grizzly Bay (D7-C); Sacramento River (D4-R, D4-L, D4-C); and eastern sites (D11-C, D19-C, D28A-L, D28A-R). Using these groupings, additional correspondence analyses were performed to further examine temporal changes in benthic species abundance and persistence and their potential causes.

Although first ordination dimension results explain the largest portion of the total deviation, examination of the second and third dimensions of ordination can reveal other meaningful patterns of response. In theory, response patterns for all ordination dimensions that explain some portion of the total variation can be examined; however, ordination

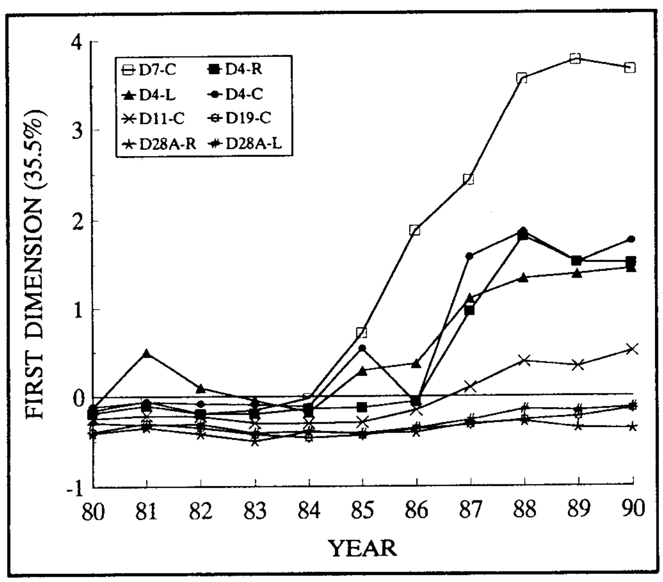

Figure 19
FIRST DIMENSION CORRESPONDENCE ANALYSIS, ALL SITES

results explaining successively smaller portions of the variation may not be meaningful. Only results from the first and second dimensions of ordination are presented here. The third dimension results typically explained less than 10% of the total deviation, probably representing random variation.

In the CA, which compared all sites, second ordination dimension results explained 14.6% of the total variation (Figure 20). With the exception of Site D7-C, responses for all sites show relatively small changes from year to year. These response patterns are thought to represent the ongoing underlying variability in benthic habitat. Constituents such as water temperature, sediment composition, and food supply and continuous processes such as tidal action all contain inherent variability that contributes to this ongoing habitat variability. This variability is thought to be the source of these species and community changes.

In contrast, a definite response in the pattern of species abundance and persistence at D7-C was detected in the second ordination dimension. The pattern and timing of this response is similar to the first dimension response suggesting similar processes are responsible.

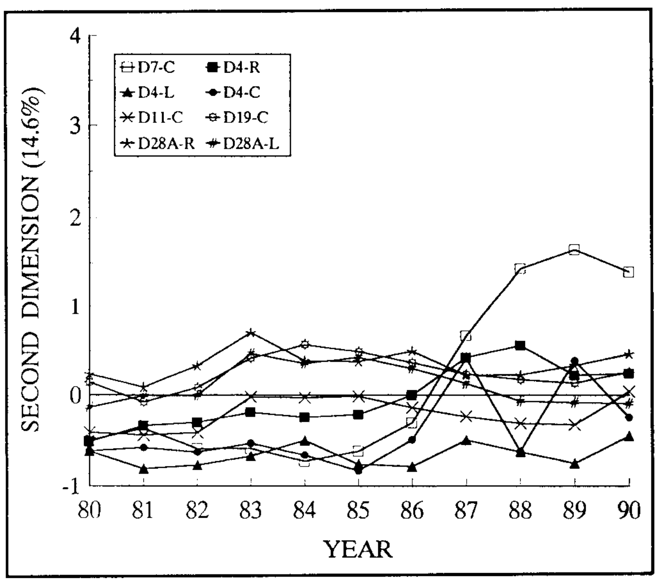

Figure 20
SECOND DIMENSION CORRESPONDENCE ANALYSIS, ALL SITES

Grizzly Bay Site, D7-C

The CA analysis for Site D7-C (Figures 21 and 22) used monthly mean abundances instead of annual means. Monthly values were used to show the patterns of variation at an individual sampling site that are a function of seasonal fluctuations in species abundance and persistence. Overall, the pattern of change shown in the first dimension results for D7-C in Figure 21 is similar to the pattern for that site seen in the analysis of all sites (Figure 19). These results show that annual mean abundance is useful for station comparisons and can also be used to show long-term community changes.

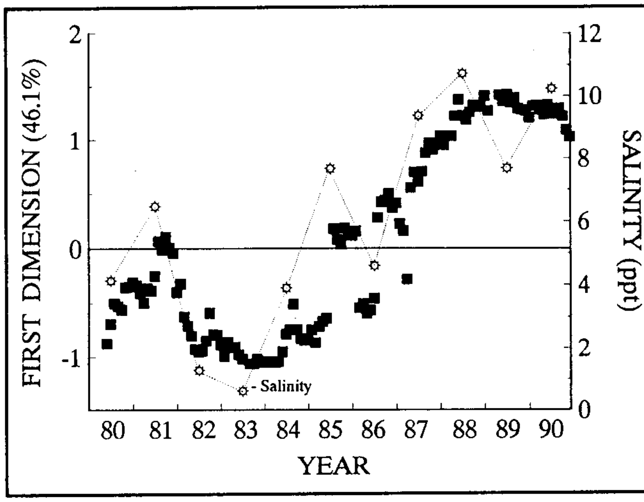

Figure 21
FIRST DIMENSION CORRESPONDENCE ANALYSIS, GRIZZLY BAY, SITE D7-C

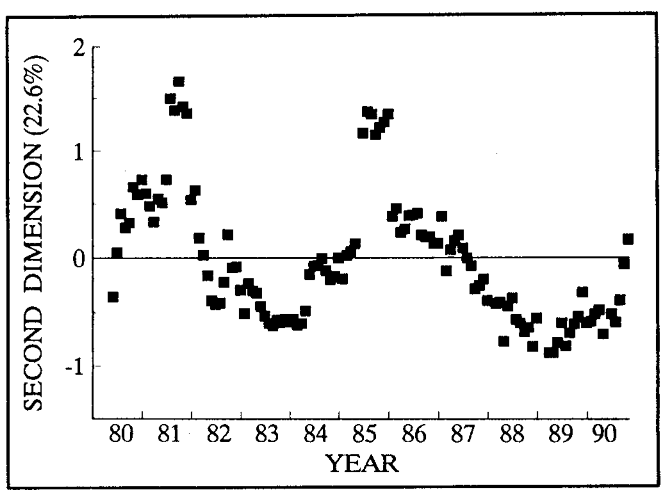

Figure 22
SECOND DIMENSION CORRESPONDENCE ANALYSIS, GRIZZLY BAY, SITE D7-C

First ordination dimension results for D7-C show species abundance and persistence oscillated between periods of rapid change and transition (1980-1982 and 1985-1988) and periods of relative stability (1982-1985 and 1988-1990) (Figure 21). With the exception of 1989, the pattern of response tracks fluctuations in mean annual salinity for the Suisun Bay region. This pattern shows little change between 1988 and 1990, even though mean annual salinity declined in 1989. However, the salinity decline was relatively small and short-lived compared to salinity fluctuations in other years. Inspection of CA and salinity curves (Figure 21) indicates a 6- to 12-month lag between changes in annual average salinity and CA score. This lag may reflect the benthos dampening the effect of short-term salinity changes. We interpret the overall pattern to reflect a response of species abundance and persistence to abiotic (salinity) and biotic (invasion of exotic species) changes.

Second dimension results for D7-C show continual oscillations in species abundance and persistence with a periodicity of 3 to 4 years (Figure 22). Patterns in the first and second dimension ordination values mirror each other from 1980 to 1986 and then become inversely related. Anomalous shifts in both first and second dimension response values occurred in 1981 and 1985. The second dimension pattern may reflect a community-level response to establishment of exotic species combined with irregular physical disturbance of the habitat such as occurred in the floods of 1983 and 1986 and the drought that persisted from 1987 through 1990.

Another way to examine the CA results is to graph the individual species scores in the first and second dimensions of ordination (Figure 23). In these graphs, with the x = zero / y = zero point as the centroid, the individual species scores indicate the influence of the species on the observed CA values through time and the relative contribution (loading) of each species to the CA value. The farther an organism is from the centroid, the greater its influence (loading) on the CA value.

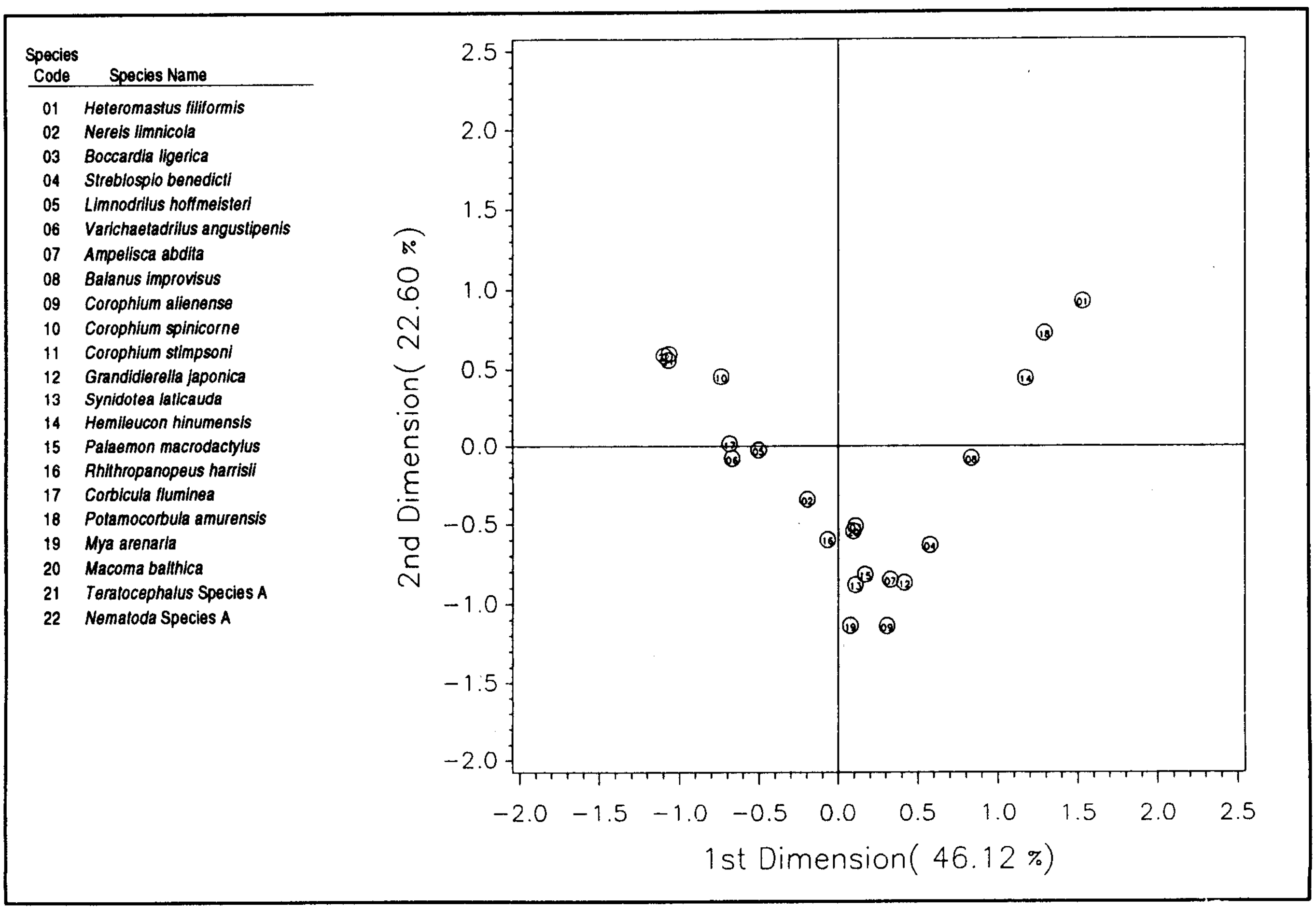

Figure 23
SPECIES SCORES, GRIZZLY BAY, SITE D7-C

For D7-C, there are essentially three groups of organisms driving the CA curves (Figure 23). Species scores for the first group are negative in the first dimension and positive in the second dimension (upper left quadrant). This group is composed of species that prefer low-salinity water and are typically most abundant in the central delta. *Corophium stimpsoni, C. spinicorne,* and *Corbicula fluminea* are principal members of this group. Presumably, organisms from this group are continually transported into Suisun Bay with the downstream currents but are only able to flourish when salinity is depressed, as occurred from 1982 to 1984.

The second group consists of organisms with both positive and negative scores in the first dimension and negative scores in the second dimension of ordination (lower left and right quadrants, Figure 23). The organisms in this group are more salt tolerant and include the species *Mya arenaria, Macoma balthica, Streblospio benedicti,* and *Ampelisca abdita*. These organisms are known to immigrate from downstream regions during periods of elevated salinity in Suisun Bay[39], as occurred in 1981 and 1985.

The third group consists of organisms with positive scores in both the first and second dimensions of ordination (upper right quadrant, Figure 23). These organisms are also more salt tolerant and include the introduced species *Hemileucon hinumensis* and *Potamocorbula amurensis*. Both of these introduced organisms became numerically dominant at D7-C in 1987.

Nichols and others[40] present evidence that establishment and eventual dominance of *P. amurensis* in Suisun Bay was principally related to the timing of the introduction and the salt-tolerant nature of the clam. A major flood in early 1986 substantially reduced the abundance of benthic species at D7-C, leaving relatively large amounts of open space. Afterward, salinity levels increased steadily through 1988 and, under normal conditions, would have resulted in colonization of the area by a suite of salt-tolerant organisms (group 2 above) from downstream regions. However, *P. amurensis*, which was apparently introduced late in 1986, was able to exploit the open habitat before resident populations could recover from the flood flows and before the salinity regime was suitable for the establishment of downstream species. Thus, the combination of the 1986 flood and the ensuing increases in salinity created an area devoid of benthic organisms and an opportunity for *P. amurensis*. Under these conditions, the clam quickly became numerically dominant throughout Suisun Bay.

A similar situation is thought to have occurred with *Hemileucon hinumensis*, a small cumacean crustacean, which was also first detected in 1986. Although *H. hinumensis* has not maintained consistently high abundance, like *P. amurensis*, it has been among the four numerically dominant organisms since 1988[41].

Between 1988 and 1990, *P. amurensis* and *H. hinumensis* were the top two numerically dominant organisms at D7-C.[42] During this time, the composition and abundance of the benthic community at D7-C appeared to stabilize (Figure 21). This stable response is believed to be a manifestation of the establishment and numerical dominance primarily of *P. amurensis* and secondarily of *H. hinumensis*, both of which appear to have very general niche requirements given their broad distribution within the estuary. These organisms have clearly benefited from the relatively stable environmental conditions that existed from 1988 through 1990 as a result of the drought.

Correlation analyses, using annual mean CA scores from the first CA dimension and annual mean values for a number of environmental variables, show that freshwater flow (as described by Sacramento River flow), salinity, and chlorophyll anomalies are significantly related to changes in benthic species abundance and persistence at D7-C (Table 8). Thus, several lines of evidence suggest changes in the benthos at D7-C are due to both abiotic (*ie*, freshwater flows and salinity) and biotic (*ie*, introduced organisms) factors. Additionally, the introduced clam affected other trophic levels, causing a significant decline in phytoplankton biomass in Suisun Bay.[43]

39 Nichols and Pamatmat, 1988; cited.

40 FH Nichols, JK Thompson, LE Schemel. 1990. The remarkable invasion of San Francisco Bay, California, USA, by the Asian clam *Potamocorbula amurensis*. II. Displacement of a former community. *Mar Biol Prog Ser* 66:95-101.

41 DWR, 1992; cited.

42 DWR, 1992; cited.

43 Alpine and Cloern, 1992; cited.

Table 8

CORRELATION ANALYSIS RESULTS[1] OF VARIOUS ENVIRONMENTAL CONSTITUENTS[2] VERSUS FIRST DIMENSION CORRESPONDENCE ANALYSIS SCORES FOR THE BENTHIC MONITORING SITES

	Sites							
Constituent	D7-C	D4-R	D4-L	D4-C	D11-C	D19-C	D28A-R	D28A-L
Sacramento River Flow	-0.64*	-0.54	-0.53	-0.53	0.32	-0.50	0.88***	0.60*
Salinity	0.78**	0.88***	0.84***	0.90***	-0.86***	-0.62*	0.49	-0.73**
Temperature	0.42	0.56	0.60	0.53	0.52	0.53	0.77**	0.45
Percent Sand	—.—	-0.31	-0.52	-0.27	—.—	0.03	-0.23	-0.38
Percent Fines (Silt and Clay)	0.11	0.35	-0.33	0.68*	-0.56	0.03	0.15	-0.02
Percent Organics	-0.59	0.42	0.38	-0.61	-0.59	0.21	-0.29	0.42
Volatile Suspended Solids	-0.08	0.14	0.03	0.10	-0.35	0.15	0.37	0.02
Chlorophyll *a* Anomaly	-0.79**	-0.56	-0.64	-0.66**	0.61*	0.60*	0.33	0.60*

1 Numbers are r values from linear correlation models. All r values were tested to determine if they differed significantly from zero. Significant r values denoted as: * 0.01 < P≤0.05; ** 0.001 < P≤0.01; ***P≤0.001.

2 Values for environmental constituents are annual means from 1980 through 1990.

Sacramento River Sites, D4-R, D4-L, D4-C

First dimension CA results for the Sacramento River sites (D4-R, D4-L, D4-C) show response patterns that are similar to the pattern for D7-C. Species abundance and persistence oscillated between periods of transition (1980-1982 and 1985-1988) and periods of relative stability (1982-1984 and 1988-1990) (Figure 24). The patterns of response in these site scores, with the exception of 1989, track the changes in the mean annual salinity for the western delta region. The patterns of response show little change between 1988 and 1990, even though mean annual salinity declined in 1989. First ordination dimension CA results explained 34.2% of the total variation.

Patterns in CA site scores for the Sacramento River sites were more dissimilar in the second dimension, which explained 21.0% of the total variation (Figure 25). CA scores were consistently positive for D4-R and consistently negative for D4-L throughout the time period. CA values for D4-C showed the largest amount of variability among the three sites after 1983. As previously discussed, fluctuations in species abundance and changes in persistent species, illustrated in the second dimension scores, are thought to occur in response to the underlying continuous habitat variability found in the natural system. Although patterns for D4-R and D4-L show that habitat variability affects the benthos at these sites, the effect is largest at D4-C. This is consistent with the highly variable physical conditions that prevail at these channel sites, particularly at D4-C.

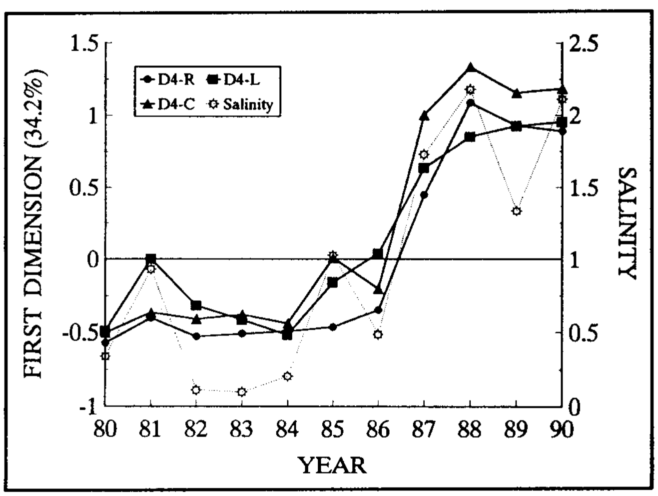

Figure 24
FIRST DIMENSION CORRESPONDENCE ANALYSIS, SACRAMENTO RIVER, STATION D4

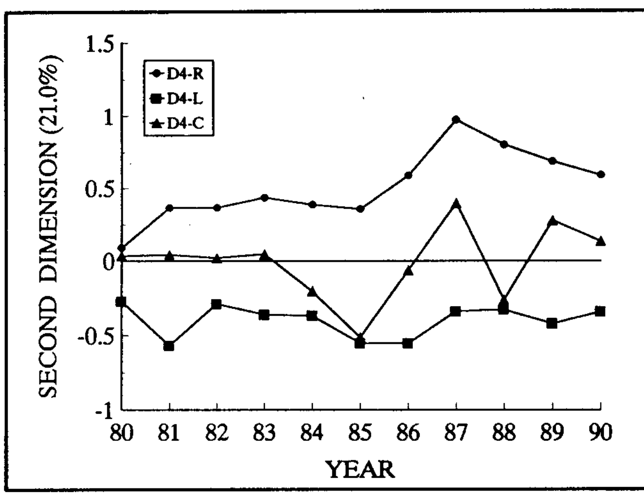

Figure 25
SECOND DIMENSION CORRESPONDENCE ANALYSIS, SACRAMENTO RIVER, STATION D4

Individual species scores for the Sacramento River sites show that three groups of species are responsible for the CA site score patterns of response (Figure 26). The first group consists of organisms with only negative scores in the first ordination dimension and both positive and negative scores in the second ordination dimension. This is the largest group and consists mostly of brackish and freshwater species such as *Corophium stimpsoni*, *Limnodrilus hoffmeisteri*, and *Manayunkia speciosa*. Various members of this group are always present at one or more of the sites.

The second group includes organisms with positive scores in the first ordination dimension and negative scores in the second ordination dimension (Figure 26). This group includes estuarine species such as *Balanus improvisus* and *Boccardia ligerica*. These estuarine species were only found at appreciable concentrations after 1986, when salinity increased and remained at higher levels. However, only *B. ligerica* has been numerically dominant since 1987.[44]

The third group includes two introduced organisms, *P. amurensis* and *H. hinumensis*, which have positive species scores in both the first and second dimensions of ordination and contribute the largest loadings (*ie*, their positions are farthest from the centroid). These organisms became numerically dominant at one or more of the Sacramento River sites after 1986.[45]

CA site scores in the first ordination dimension and the individual species scores for the Sacramento River sites show a pattern in the benthos that is very similar to the one observed for D7-C. Between 1980 and 1986, patterns varied in relation to changes in salinity. The floodflows in 1986 substantially reduced population abundances, resulting in relatively large amounts of open space.

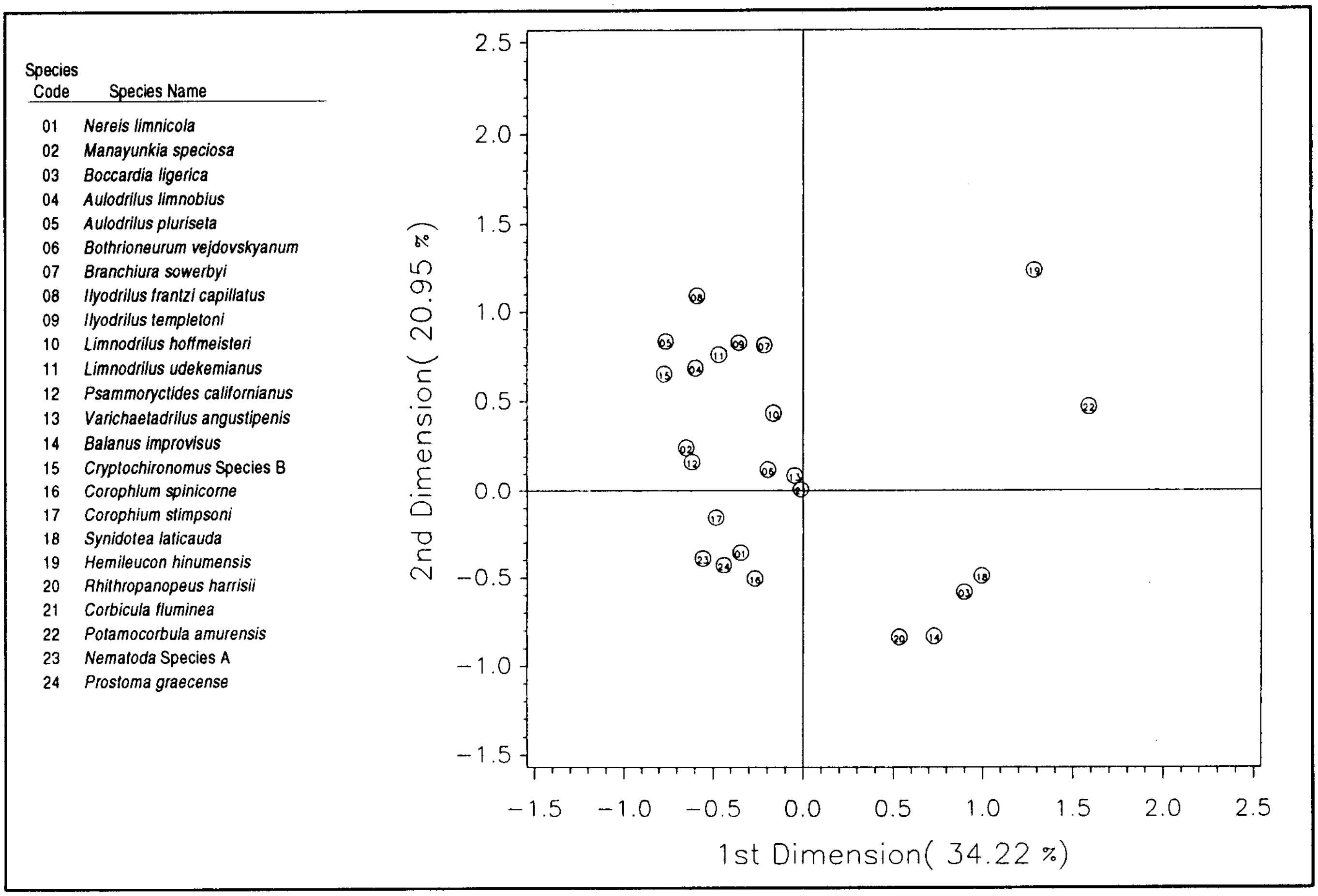

Figure 26
SPECIES SCORES, SACRAMENTO RIVER, STATION D4

44 DWR, 1992; cited.
45 DWR, 1992; cited.

Drought-associated increases in salinity, beginning in 1987, limited the recolonization of resident brackish water species. Meanwhile, *P. amurensis* and *H. hinumensis* were rapidly colonizing Suisun Bay. In relatively stable environmental conditions, these exotic organisms, along with other resident species (particularly *Corbicula fluminea*), were able to colonize the Sacramento River sites. Patterns of response for CA scores from all three sites showed little change after 1988. The persistent dominance of *P. amurensis*, *H. hinumensis*, and *C. fluminea* appears to have resulted in a new and stable benthic community at the Sacramento River sites. The species composition of this new community, however, is substantially different from the community observed at D4 in the early 1980s.

Correlation analyses show a significantly positive relationship between salinity and CA scores at all D4 sites (Table 8). Sacramento River flow is negatively related to species abundance and persistence at all D4 sites, but the relationship is not significant. The percentages of silt and clay were significantly related to benthic species abundance and persistence only at D4-C. A significantly negative relationship between chlorophyll *a* concentration and benthic species abundance and persistence at D4-C may be due to the presence of both *P. amurensis* and *C. fluminea*.

In general, the channel environment of D4 is more variable than the shoal region of Grizzly Bay or the lacustrine environment of Sherman Lake (D11) and Franks Tract (D19). This is particularly true for sediment composition. Nevertheless, fluctuations in sediment composition appear to have played a primary role in determining the pattern of benthic species abundance and persistence only at the center of D4 but not at the banks. Overall, results suggest that salinity had the broadest and most significant influence on benthic species abundance and persistence at D4 (Table 8). Thus, as with D7-C, both abiotic (salinity and sediment composition) and biotic (invasion of exotic species) processes have acted to alter the benthos at D4.

Eastern Sites, D11-C, D19-C, D28A-L, D28A-R

CA results for the first dimension from the third group of sites (eastern sites D11-C, D19-C, D28A-L, D28A-R) show response patterns that differ from those for the other two site groups (Figure 27). First dimension CA results explained 25.4% of the total variation. In general, response patterns in the first dimension, with the exception of values for D11-C, showed little change over time. The pattern for D11-C showed little change between 1980 and 1985 but moved steadily downward thereafter. None of these response patterns track the trend in average annual salinity for this region.

Response patterns for CA results in the second dimension were more evident, although only 17.6% of the total sample variation was explained (Figure 28). CA site scores for all sites showed a consistent pattern of change from 1980 through 1990. Between 1980 and 1982, CA scores were stable, with little fluctuation among years or sites. However, a

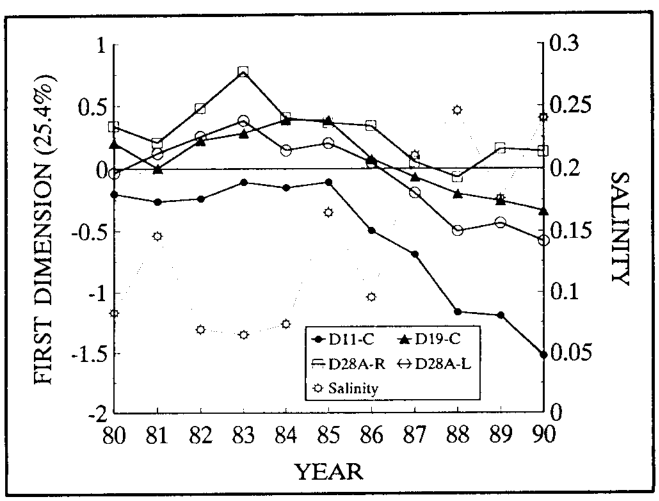

Figure 27
FIRST DIMENSION CORRESPONDENCE ANALYSIS, EASTERN STATIONS, D11, D19, AND D28A

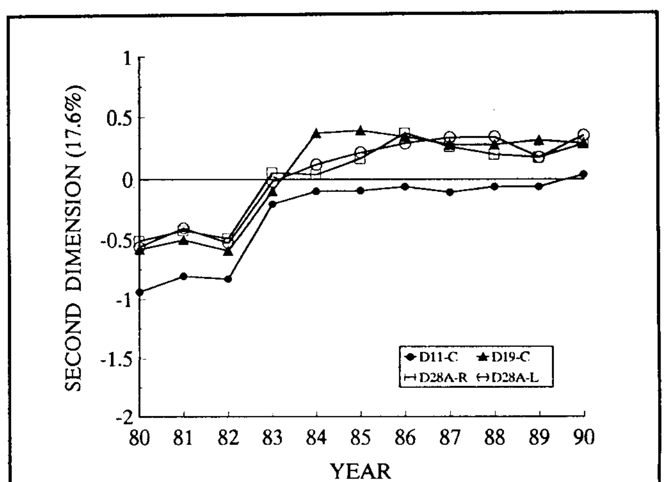

Figure 28
SECOND DIMENSION CORRESPONDENCE ANALYSIS, EASTERN STATIONS, D11, D19, AND D28A

major shift occurred in CA scores for all of the eastern sites from 1982 to 1984. This shift occurred over a relatively short time and led to establishment of a new and stable benthic community. These response patterns may be due to habitat changes that were not measured by the monitoring program.

Individual species scores for the eastern sites show that, with the exception of *Hemileucon hinumensis*, no one species overwhelmingly influenced the patterns of CA scores in the first or second dimension of ordination (Figure 29). Within this group of sites, *H. hinumensis* has only been collected from D11-C and only since 1987. This suggests the presence of *H. hinumensis* at D11-C is at least partly responsible for the negative trend in the first dimension CA scores for this site.

Results of correlation analyses show freshwater flow, salinity, and chlorophyll *a* concentration were all significantly related to benthic species abundance and persistence at one or more of the eastern sites (Table 8). Water temperature showed a positive relationship ($P<0.05$) with benthic species abundance and persistence, but only for D28A-R. The significantly positive relationship between first ordination dimension CA results and chlorophyll *a* concentrations may be related to temporally matched seasonal increases in benthos abundance and phytoplankton biomass. Although the first dimension ordination patterns for the eastern sites differed from those for the other site groups, the same factors, namely salinity and freshwater flow, are thought to have had the largest effect on benthic species abundance and persistence at the eastern sites. Based on the limited change in CA scores for the eastern sites and the limited distribution among individual species scores, changes in salinity and freshwater flow appear to have influenced species abundance more than species persistence.

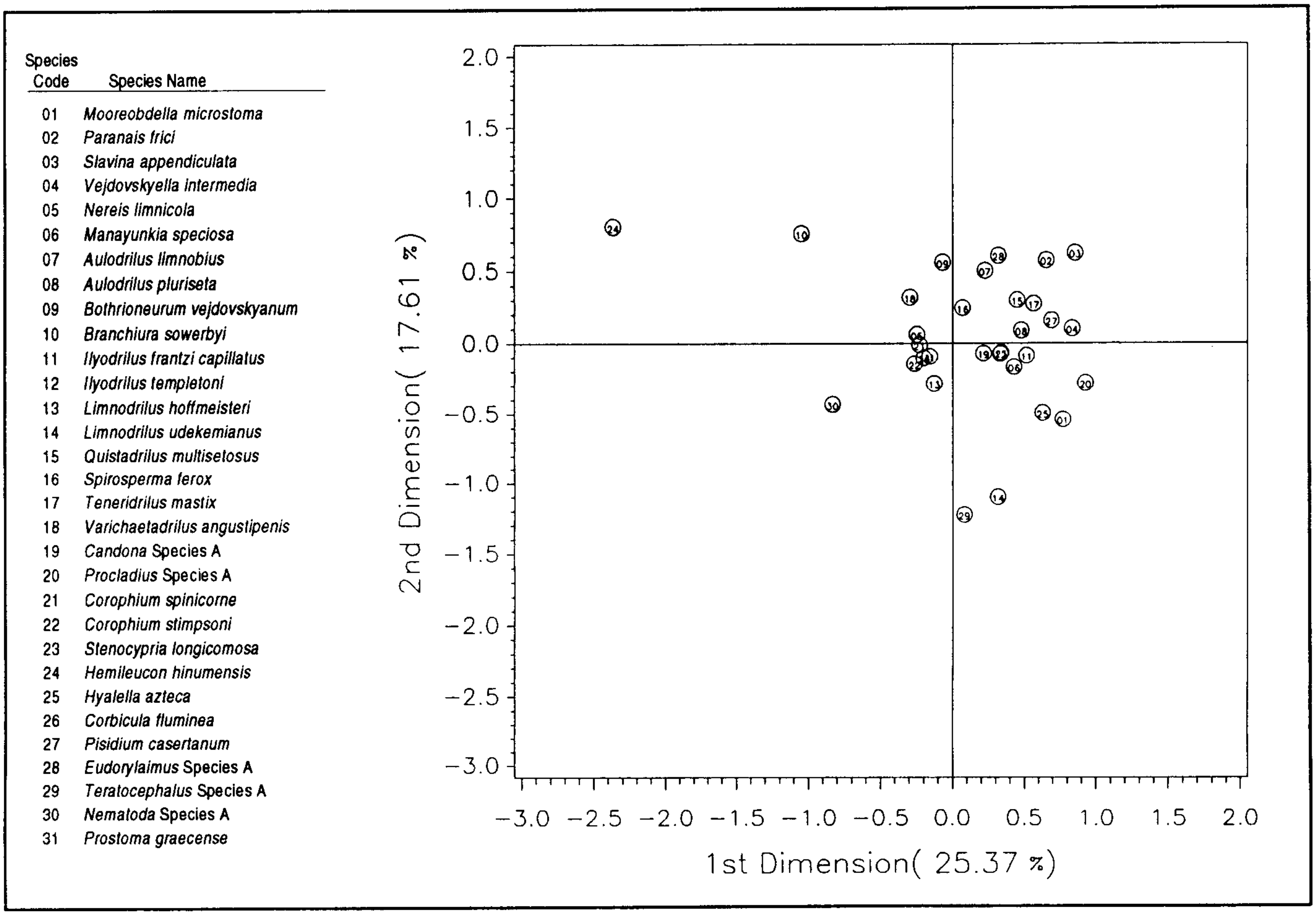

Figure 29
SPECIES SCORES, EASTERN STATIONS, D11, D19, AND D28A

Persistent and Dominant Species

A major finding from the correspondence analysis is that a relatively small number of numerically dominant and persistent species have a large influence over the composition of the benthos in the upper Sacramento-San Joaquin estuary. In her report, Markmann[46] discusses the life history and population patterns of the most numerous benthic organisms. She found that of the 140 benthic species identified from 1975 to 1981, only about 13 species typically comprised 10% or more of the community density at any one site. The suite of species that dominated the sampling area from 1980 to 1990 changed little from the suite of species that dominated from 1975 to 1981.

This section begins with a status review and update of the persistent and dominant species discussed by Markmann. A discussion of three exotic benthic organisms (*P. amurensis, H. hinumensis, Gammarus daiberi*) detected from 1980 to 1990 follows this review.

Limnodrilus hoffmeisteri and Varichaetadrilus angustipenis

These oligochaete worms are both in the family Tubificidae. In fact, until 1989, both species were classified as members of the genus *Limnodrilus*. These worms are able to withstand extreme environmental changes and can tolerate polluted conditions and hypoxic sediments.[47] Temperature (primarily) and substrate composition (secondarily) have been shown to regulate reproduction and recruitment.[48,49] Above temperatures of 15°C, breeding is continuous. Recruitment success is optimal in organically rich mud.[50] Crumb[51] found a relationship between the annual temperature and population abundance of *L. hoffmeisteri* in the Delaware River. Abundances were highest during the spring, when temperatures ranged from 20–25°C at sites with high concentrations of organic mud.

In this estuary, either or both *L. hoffmeisteri* and *V. angustipenis* were among the four numerically dominant species at every monitoring site from 1980 to 1990 (Appendix B). Abundances were variable within and among sites, but were often highest at D11-C. Markmann reported *Limnodrilus* spp. as the most numerous organism at D7-C from 1975 to 1981. While *L. hoffmeisteri* maintained numerical dominance at D7-C through June 1983, it declined in abundance in 1984 and remained at lower levels thereafter (Appendix B).

The broad distribution of both *L. hoffmeisteri* and *V. angustipenis* within the sampling area is evidence of the robust nature of these species. Salinity levels often differ by an order of magnitude between Suisun Bay and the central delta. *L. hoffmeisteri* and *V. angustipenis* are among the few native benthic organisms that have maintained their numerical dominance and broad distribution throughout the existence of this monitoring program.

Corophium stimpsoni and C. spinicorne

Corophium spp. are native tube-building detritivorous amphipods most prevalent in areas with moderate levels of fine sediments and organic material and slightly brackish to fresh water.[52] These amphipods are reported to be a food source for other arthropods, such as *Crangon franciscorum*, and several estuarine fishes such as striped bass, *Morone saxatilis*, and catfish, *Ictalurus* spp.[53]

46 Markmann, 1986; cited.

47 RO Brinkhurst. 1972. *The Role of Sludge Worms in Eutrophication*. US Environmental Protection Agency, Ecol Res Serv EPA-R3-72-004. 68 pp.

48 Brinkhurst, 1972; cited.

49 CR Kennedy. 1966. The life history of *Limnodrilus hoffmeisteri* Clap. (Oligochaeta: Tubificidae) and its adaptive significance. *Oikos* 17:158-168.

50 Brinkhurst, 1972, and Kennedy, 1966; cited.

51 SE Crumb. 1977. Macrobenthos of the tidal Delaware River between Trenton and Burlington, New Jersey. *Chesapeake Sci* 18:253-265.

52 Nichols and Pamatmat, 1988; cited.

53 Markmann, 1986; cited.

Historically these amphipods have been the numerically dominant benthic organism in many parts of the delta, often exceeding concentrations of 20,000 individuals per square meter.[54,55,56] From 1980 to 1990, abundances appear to have varied seasonally, with peak concentrations occurring between summer and fall (Appendix B). However, in 1987 abundance of both *C. stimpsoni* and *C. spinicorne* declined sharply at all Sacramento River sites (D4-L, D4-R, D4-C) and remained at extremely low levels through 1990. Markmann suggested that specific conductance above 5,000 µS/cm (2.8 ppt) may limit the occurrence of *C. stimpsoni*. An examination of the relationship between *C. stimpsoni* abundance and specific conductance at D11-C supports this hypothesis (Figure 30). In general, the abundance of *C. stimpsoni* was depressed when specific conductance exceeded 4,000 µS/cm (2.3 ppt). Between 1987 and 1990, specific conductance at D4 exceeded 4,000 µS/cm 68% of the time. These drought-associated increases in specific conductance (salinity) appear to have limited the occurrence of at least *C. stimpsoni* in the western delta and illustrate the effect physicochemical changes can have on native benthic organisms.

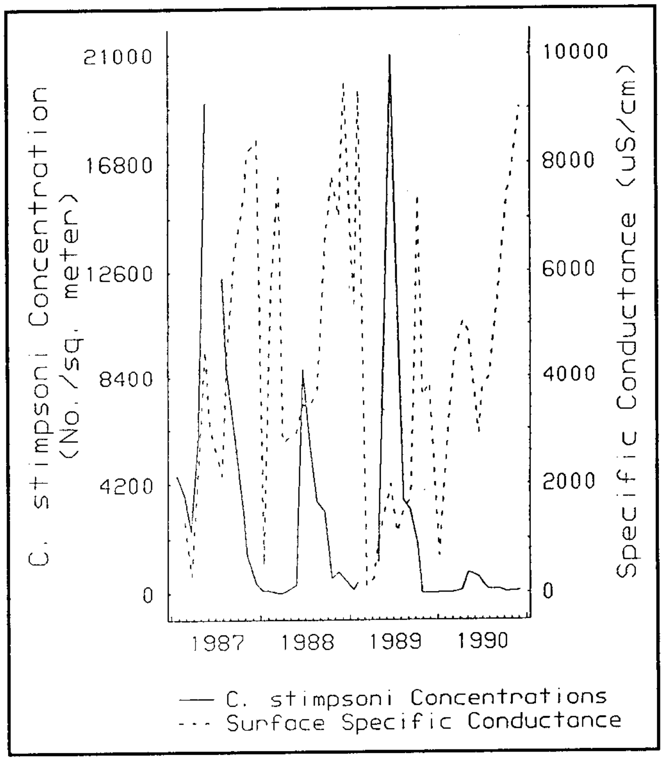

Figure 30
***COROPHIUM STIMPSONI* CONCENTRATIONS AND MONTHLY SPECIFIC CONDUCTANCE AT D11-C, 1987-1990**

Manayunkia speciosa

Manayunkia speciosa is a colonial tube-building polychaete worm commonly found in fresh water.[57] *M. speciosa* is hermaphroditic and reproduces sexually or asexually within its tube.[58] The tube is constructed of fine particles cemented together by a mucoid secretion.[59] The young mature in the parental tube and crawl out as small adults to form their own tube within the colony.[60]

Hazel and Kelley[61] first reported the presence of *M. speciosa* along the West Coast from samples taken in the San Joaquin River and one location in Oregon. DWR benthic monitoring samples collected from 1975 to 1979 showed *M. speciosa* to exist at several locations in the interior delta at concentrations from 2,000 to 50,000 individuals per square meter.[62] From 1975 to 1979, the greatest number of *M. speciosa* were found in the lower Mokelumne and San Joaquin rivers and at D28A on Old River.[63]

54 CR Hazel and DW Kelley. 1966. Zoobenthos of the Sacramento-San Joaquin Delta. Pages 113-132 in *Ecological Studies of the Sacramento-San Joaquin Estuary, Part I, Zooplankton, Zoobenthos, and Fishes of San Pablo and Suisun Bays, Zooplankton and Zoobenthos of the Delta*. DW Kelley, editor. Department of Fish and Game, Fish Bulletin 136.

55 L Eng. 1975. *Biological Studies of the Delta-Mendota Canal, Central Valley Project, California II*. California Academy of Science, Contract 14-06-200-7762A. 178 pp.

56 Markmann, 1986; cited.

57 TP Poe and DC Stefan. 1974. Several environmental factors influencing the distribution of the freshwater polychaete, *Manayunkia speciosa* Leidy. *Chesapeake Sci* 15:235-237.

58 P Croskery. 1978. The freshwater co-occurrence of *Eurytemora affinis* (Copepoda: Calanoida) and *Manayunkia speciosa* (Annelida: Polychaeta): possible relics of a marine incursion. *Hydrobio* 59:237-241.

59 Poe and Stefan, 1974; cited.

60 Croskery, 1978, and Poe and Stefan, 1974; cited.

61 Hazel and Kelley, 1966; cited.

62 Markmann, 1986; cited.

63 Markmann, 1986; cited.

From 1980 to 1990, *M. speciosa* was numerically dominant at D19-C and D28A-R. Abundance at D19-C fluctuated between zero and 10,000 individuals per square meter from 1980 to 1985 but remained below 2,000 thereafter (Appendix B). Abundance at D28A-R was much more variable, ranging from zero to 36,000 individuals per square meter from 1980 to 1990. Abundance was highest during the extremely wet years of 1983 and 1986. Numerical dominance of *M. speciosa* at D19-C and D28A-R suggests this polychaete prefers freshwater habitats where the substrate is dominated by fine material.

Corbicula fluminea

The freshwater clam *Corbicula fluminea* was the most common benthic organism collected in the sampling area. This clam was introduced into California in the late 1940s and quickly became a dominant member of the benthos in the upper estuary.[64] From 1980 to 1990, *C. fluminea* was among the four numerically dominant organisms at all sampling sites except D7-C (Appendix B).

The ecology and biology of *C. fluminea* have been thoroughly studied by researchers throughout the world. Only a brief summary is presented here; refer to Mattice *et al*[65] for additional information. *C. fluminea* is a suspension-feeding clam that filters phytoplankton and organic detritus from the water column.[66] More recent studies suggest that, like *Potamocorbula amurensis*, high concentrations of *C. fluminea* are able to filter a significant portion of the phytoplankton from the water column.[67] Reproduction in the Sacramento-San Joaquin estuary is thought to occur twice annually between spring and fall.[68,69] Adult clams brood their larvae in a marsupium for about one month.[70] Larvae are released from the marsupium when temperatures exceed 15°C.[71] Released larvae settle out within 48 hours.[72]

Immature clams are readily dispersed to other parts of the estuary by flowing water.[73] *C. fluminea* have been collected at D7-C, but it is thought these clams are brought in during times of increased outflows.[74] Salinity levels in Suisun Bay prevent establishment of permanent populations.[75] Markmann[76] suggested *C. fluminea* populations in the central delta serve as recruitment pools for the western delta, where immature clams are transported downstream during high outflows in the spring. She believed higher salinity levels in the fall, followed by increased water velocities in winter and spring, prevent establishment of large, permanent populations of *C. fluminea* in the western delta. However, benthic monitoring data from 1980 to 1990 suggest established populations of *C. fluminea* do exist in the western delta. Although abundance in the western delta was generally lower than in the central delta, clams were continually collected at both D4 and D11 during years of extremely high outflow (1983 and 1986) and during drought years (1987 to 1990) when salinity levels increased in the western delta. In addition to the lower abundance of clams in the western delta, Winternitz[77] found the productivity of *C. fluminea* was lower in the western delta than in the central delta. The western delta is probably marginal habitat for *C. fluminea*, primarily due to the higher salinity levels.

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64 DS Cherry, J Cairns, RL Graney. 1980. Asiatic clam invasion causes and effects. *Water Spectrum* Fall:19-24.

65 JS Mattice, LL Eng, BN Collier. 1979. *Corbicula 1979: A Bibliography*. Environmental Sciences Division, Oak Ridge National Laboratory. Publication 1315.

66 Eng, 1975;cited.

67 R Cohen, PV Dresler, E Phillips, R Cory. 1984. The effect of the Asiatic clam *Corbicula fluminea* on phytoplankton of the Potomac River, Maryland. *Limnol Oceanogr* 29:170-180.

68 L Eng. 1977. Population dynamics of the Asiatic clam, *Corbicula fluminea* (Muller), in the concrete-lined Delta-Mendota Canal of central California. Pages 40-68 in *Proc First Intl Corbicula Symp, October 13-15, 1977*.

69 Hazel and Kelley, 1966; Siegfried *et al*, 1978; Eng 1975; cited.

70 Eng, 1977; cited.

71 Crumb, 1977; cited.

72 PV Dresler and RL Cory. 1980. The Asiatic clam, *Corbicula fluminea* (Muller), in the tidal Potomac River, Maryland. *Estuaries* 3:150-151.

73 Eng, 1977; cited.

74 Hazel and Kelley, 1966; cited.

75 Hazel and Kelley, 1966; cited.

76 Markmann, 1986; cited.

77 L Winternitz. 1992. *Estimating Secondary Production Level of Corbicula fluminea in the Sacramento-San Joaquin Estuary*. Masters Thesis. University of San Francisco.

Potamocorbula amurensis

The Asian clam, *Potamocorbula amurensis*, first detected in this estuary in late 1986, is thought to have been introduced into Suisun Bay as larvae from ship ballast water.[78] This clam is native to estuaries along the east coast of Asia.[79] The abundance and distribution of *P. amurensis* has increased dramatically in the upper Sacramento-San Joaquin estuary, since it was first detected.[80,81] By 1990 (four years after first detection), *P. amurensis* was well established in a variety of habitats throughout San Pablo and Suisun Bays, and Suisun Marsh, often at concentrations exceeding 1,000 clams per square meter.[82]

Results from the correspondence analyses clearly show *P. amurensis* has altered the benthos at both D7 and D4. This clam has been a numerically dominant organism at both stations since 1988.[83] However, the persistently low salinity in the central delta has probably prevented the establishment of *P. amurensis* in this region. Although this clam is reported to be euryhaline,[84] laboratory observations of *P. amurensis* confirm that they cease all activity when exposed to freshwater and exhibit a high rate of mortality after several weeks of such exposure.[85]

Trophic dynamics within the upper estuary have been altered by the introduction of the Asian clam. In particular, *P. amurensis* is known to have contributed to the substantial and sustained reductions in surface chlorophyll *a* concentrations in Suisun Bay.[86] This clam is a suspension feeder capable of consuming phytoplankton, bacterioplankton, particulate organic matter, and zooplankton nauplii.[87,88] Although the establishment of *P. amurensis* may have increased the competition between other benthic organisms for space and food, it does provide a new and abundant food source for bottom feeding birds, fish, and crabs.[89]

Gammarus daiberi

The amphipod *Gammarus daiberi* is endemic to much of the Atlantic coast, commonly occurring in estuaries and sounds from New York through South Carolina.[90] Populations reach highest concentrations during spring and summer in salinities of 1–5 ppt; however, individuals do occur seaward to salinities of 15 ppt. Gammarid species are typically macrophagous and free-swimming. *G. daiberi* is pelagic, occurring in mid- to near-bottom depths, but may also reside epibenthically. The species co-occurs with *G. fasciatus* and *G. tigrinus* in tidal areas of fresh and brackish water. The life history and habitat requirements of *G. daiberi* have not been studied in its Pacific coast setting, but they are presumed to be similar to its native ecology.

G. daiberi was first detected in this estuary in 1983 from benthic samples collected in the central delta. Between 1983 and 1986 the amphipod was collected only rarely. Beginning in 1986, however, appreciable concentrations of *G. daiberi* were collected in both benthic and zooplankton monitoring samples. Since 1986, *G. daiberi* has been routinely collected in the central and western delta regions, and in Suisun Bay. Abundance fluctuates seasonally, with highest concentrations typically occurring in spring and early summer. Because of this amphipod's mobility, estimates of benthic concentrations are subject to

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78 JT Carlton, JK Thompson, LE Schemel, FH Nichols. 1990. The remarkable invasion of San Francisco Bay (California, USA) by the Asian clam *Potamocorbula amurensis*. I. Introduction and dispersal. *Mar Ecol Prog Ser* 66:81-94.

79 Carlton *et al*, 1990; cited.

80 Carlton *et al*, 1990; cited.

81 ZP Hymanson. 1992. *Results of a Spatially Intensive Survey for Potamocorbula amurensis in the Upper San Francisco Bay Estuary*. Interagency Ecological Studies Program, Technical Report 30. Department of Water Resources.

82 Hymanson, 1992; cited.

83 DWR, 1992; cited.

84 Carlton *et al*, 1990; cited.

85 F Nichols, US Geological Survey, Palo Alto, CA; personal communication. 1993.

86 Alpine and Cloern, 1992; cited.

87 I Werner and JT Hollibaugh. *Potamocorbula amurensis* (Mollusca, Pelecypoda): Comparison of clearance rates and assimilation efficiencies for phytoplankton and bacterioplankton. *Limnology and Oceanography* 38:949-964. 1993.

88 Kimmerer, personal communication.

89 Alpine and Cloern 1992, Carlton *et al* 1990, Nichols *et al* 1990; all cited.

90 EL Bousfield. *Shallow-Water Gammaridean Amphipoda of New England*. Comstock Publisher Associates, Ithaka, NY. 1973.

considerable error. However, benthic and zooplankton monitoring show *G. daiberi* is well established throughout much of the upper estuary. This amphipod is known to serve as a food source for young striped bass.[91]

Hemileucon hinumensis

The cumacean crustacean *Hemileucon hinumensis* was first detected in Suisun Bay in 1986. Little is apprently known about the ecology of this organism. No information on this species' ecology or life history was found in a search of recent literature. The abundance and distribution of *H. hinumensis* increased between 1986 and 1990, a period coincident with increased abundance and distribution of other exotic species, such as *Potamocorbula amurensis* and *Gammurus daiberi.* The coincident appearance and establishment of these introduced species, suggests the presence of related ecological requirements that probably originated during the drought. Research efforts into the resulting interactions and effects of *H. hinumensis* on the resident benthic community may provide new clues to the species' ecology and role in the benthic community.

Trends in the Benthos and Water Project Operations

Markmann[92] concluded that water project operations could affect the benthos of the upper estuary through changes in seasonal salinity patterns and localized changes in water velocity and sediment dynamics. It is clear that seasonal salinity patterns do affect the benthos of the upper estuary. However, this summary analysis showed that from 1980 through 1990 most of the substantial variability in the benthos was due to longer-term (drought and flood mediated) changes in salinity.

Determination of water project related impacts on the benthos was not included as a specific criterion in the design of this monitoring program. Such a criterion would require a substantially different program design. The hydrology of the upper estuary is very complex, while water project operations are both spatially and temporally variable. We think focused modeling and field studies are required to determine if and what effects water project operations are having on the benthos of the upper estuary.

Detectability and Sensitivity Analysis of the Benthic Monitoring Program

Further analyses of the benthic data collected from 1980 to 1990 were completed to determine the ability of the existing monitoring program to detect changes in benthic community structure. Our approach in this section is to answer three questions that are key to the design and implementation of a benthic monitoring program with current objectives to:

- Meet the monitoring obligations described in Water Rights Decision 1485.
- Monitor trends in the abundance and distribution of benthic fauna.
- In conjunction with other monitoring data, determine what environmental factors (including water project operations) are responsible for the trends in abundance and distribution of benthic fauna.

What should the sampling frequency be?

Data collected from 1980 to 1990 were analyzed to determine the variance structure of organism abundance at the eight benthic sampling sites. Coefficients of variation

$$CV = [(standard\ deviation/mean)100]$$

were used as a standardized measure of variance. CVs were calculated using total community abundance values over three time intervals: month, season (3 months), and year. Results show total abundance was highly variable at all sites over all time periods (Table 9). Within each period, the CVs among sites were similar, however, demonstrating that the magnitude of variation is similar throughout the sampling region.

CV results for total community abundance were also used to generate power curves. These curves show the number of samples needed to detect various levels of change in community abundance (expressed as percentages) on a yearly, seasonal, and monthly basis. Currently, the monitoring program

91 L Miller, Department of Fish and Game, Stockton, CA; personal communication, 1993.
92 Markmann, 1986; cited.

Table 9
COEFFICIENTS OF VARIATION FOR TOTAL COMMUNITY ABUNDANCE VALUES AND FOR *CORBICULA FLUMINEA* ABUNDANCE VALUES CALCULATED FOR DIFFERENT SITES AND TIME INTERVALS

	Total Community Abundance		
Site	Year CV	Season CV	Month CV
D7-C	246	286	302
D11-C	283	286	304
D4-R	253	247	313
D4-L	291	286	306
D4-C	264	340	400
D19-C	264	226	238
D28A-R	267	279	289
D28A-L	347	272	331

	Corbicula Fluminea Abundance		
Site	Year CV	Season CV	Month CV
D7-C	79.8	160	222
D11-C	78.4	103	113
D4-R	114	101	125
D4-L	115	139	142
D4-C	120	152	158
D19-C	69.1	93.5	108
D28A-R	82.1	138	140
D28A-L	129	135	173

collects three replicate samples at each site, each month. Thus, nine samples are collected during a season and 36 samples are collected at each site during a year. Results from the power curve analysis for D7-C show that at the current sampling frequency the monitoring program is able to detect a 55% change in total abundance between years but is not able to accurately detect quantitative changes between months or seasons (Figure 31). Results of power curve analyses for other sites (not shown) were similar because of the similarity in CV results.

CVs were also calculated for several prominent benthic organisms. Results for *Corbicula fluminea*, the most prominent organism throughout the sampling region from 1980 to 1990, are shown in Table 9 and exemplify results for other species tested. Although substantial variability in the abundance of a single species also exists, CVs for all sites and time periods were lower for *C. fluminea* than for the total community abundance values (Table 9). This suggests the monitoring program is better able to detect abundance changes in prominent species. However, power curve analyses show increased sensitivity in detecting the change in abundance of a single species is limited to the yearly and seasonal time period. For example, results from Site D19-C, where variation in *C. fluminea* was lowest for all periods, show the current level of sampling is able to detect somewhat less than a 30% difference in abundance between years and about a 50% difference between seasons. No quantitative difference could be detected between months (Figure 32).

As an alternative to monitoring the abundance and distribution of all macrobenthic organisms, the program could be structured to monitor only the abundance and distribution of dominant species. Fluctuations in abundance of the more persistent organisms, which tend to be lower, would allow for a reduction in sampling effort. However, any reduction in sampling frequency would compromise the ability to detect seasonal or annual abundance changes and other basic life-history information and further reduce the ability to characterize abundance and distribution trends in less persistent but ecologically important species.

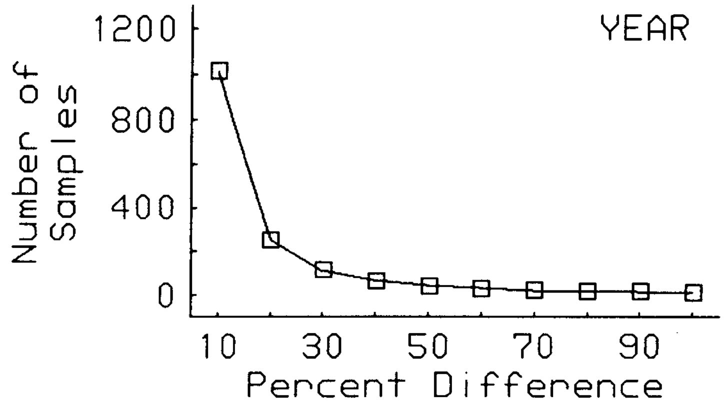
What should the sample replication be?

Altering the number of sample replicates is another way to change the level of sensitivity and detectable difference. Currently, three replicate samples are collected monthly at each site. This is the minimum required to obtain quantitative monthly abundance estimates, because of the high variability in abundance. As discussed, power of detection curves show the benthic monitoring program is at the lower limits of detection on a monthly or seasonal time scale and at the mid-detection level on an annual scale.

Any increase in the number of replicates could increase the detection levels at all time scales. However, a substantial increase in the number of replicates would be required if the sampling frequency were less than monthly, because sensitivity of the monitoring program is based on the total number of samples collected at a site. For example, suppose sampling frequency were reduced from monthly to quarterly and the number of replicates remained the same. This would reduce the total number of samples collected annually at each site from 36 to 12. From the results in Figure 31 it can be seen that this reduced sampling frequency would only provide the ability to detect a 90% difference in total community abundance between years. On the other hand, maintaining the same level of detectability

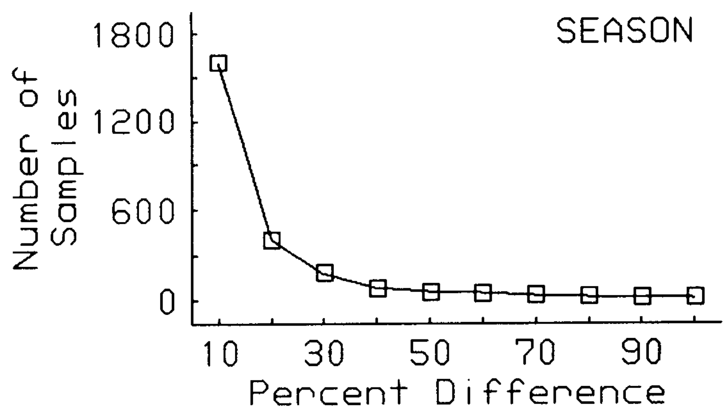
YEAR

Percent Detectable Difference	Number of Samples
10	1012
20	253
30	112
40	63
50	40
60	28
70	20
80	16
90	13
100	10



SEASON

Percent Detectable Difference	Number of Samples
10	1598
20	400
30	178
40	81
50	52
60	45
70	33
80	25
90	20
100	16



MONTH

Percent Detectable Difference	Number of Samples
10	1522
20	381
30	169
40	95
50	61
60	42
70	31
80	24
90	19
100	15

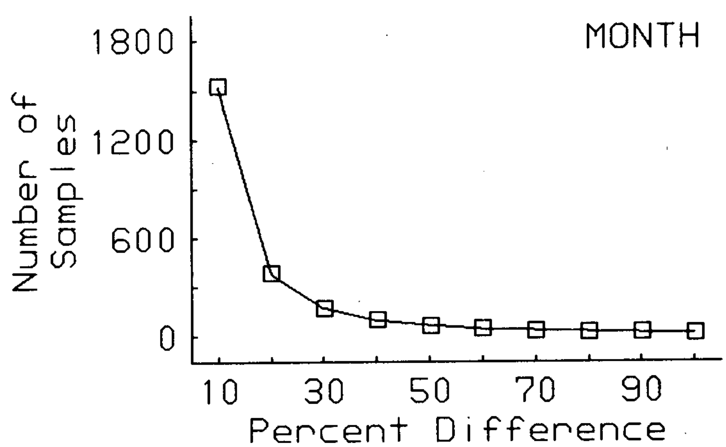
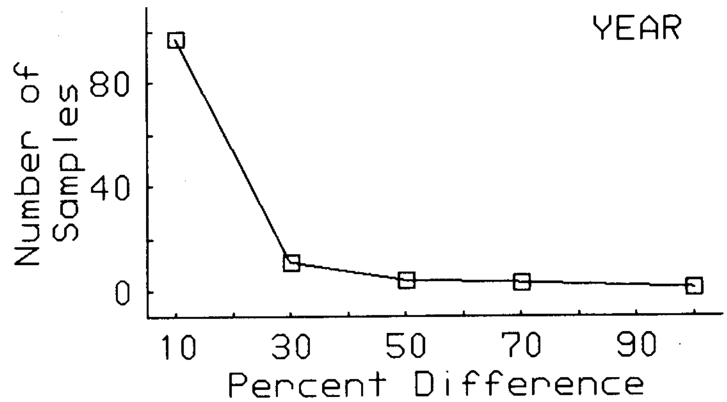


Figure 31
POWER OF DETECTION CURVES FOR TOTAL COMMUNITY ABUNDANCE AT D7-C

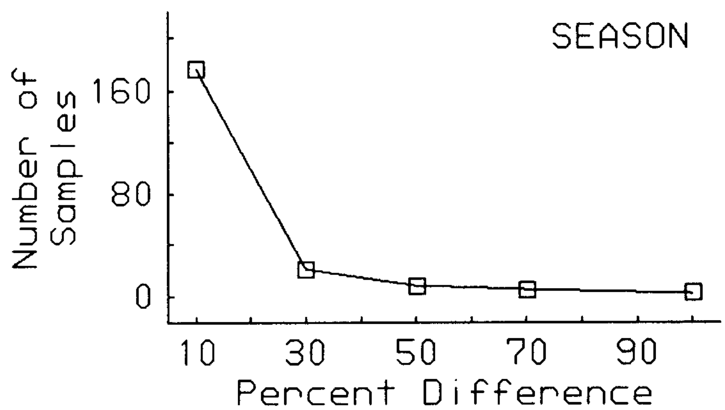
YEAR

Percent Detectable Difference	Number of Samples
10	97
30	11
50	4
70	3
100	1



SEASON

Percent Detectable Difference	Number of Samples
10	176
30	20
50	7
70	4
100	2



MONTH

Percent Detectable Difference	Number of Samples
10	217
30	24
50	9
70	6
100	3

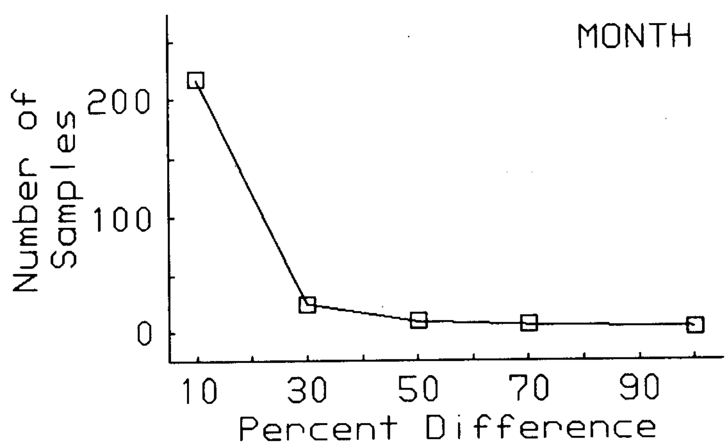


Figure 32
POWER OF DETECTION CURVES FOR *CORBICULA FLUMINEA* AT D19-C

between years (*ie,* about 55%) would require collection of nine replicate samples from each site each quarter. Thus, while detecting differences in abundance between months or seasons is not a primary objective, collecting three replicate samples each month provides a level of effort consistent with all objectives. In addition, no amount of increase in sample replication could replace the loss of life history information if the sampling frequency were less than monthly. Collecting samples on at least a monthly basis is essential to monitoring recruitment events.

What should the spatial distribution of stations be?

A variety of procedures can be used to determine the location of benthic sampling stations. One simple and objective way is to choose locations where the maximum chance of collecting a species occurs. Presumably, the presence and persistence of a benthic organism at any one location is based on the characteristics and variability of the local environment. The presence or absence of a species and subsequent changes in abundance are a reflection of changes in the environment. By choosing to sample sites with maximum species diversity, we increase the chance of detecting the response of benthic organisms to changes in the environment. However, detection of new introductions is an exception to this line of reasoning, since we have no idea which organisms are going to be introduced or where they will be introduced.

Correspondence analyses of all sites together suggest the existing sites fall into one of three groups based on benthic species abundance and persistence. The results are fairly intuitive, given the spatial distribution of the sites, and they provide an objective basis for making comparisons among sites.

Since 1980, D7-C has been the only site sampled in the Suisun Bay region. Due to the large fluctuations in salinity and the recent establishment and dominance of two exotic organisms, *Potamocorbula amurensis* and *Hemileucon hinumensis,* this region is distinct from the two delta regions sampled. D7-C is, by default, the best site to sample in the future, because it is the only site in this region.

The second region consists of three sites in the lower Sacramento River: D4-R, D4-L, and D4-C. Together these sites form a transect across the river where samples are taken from the right and left banks and center channel. Comparisons of species occurrence at these sites show more species have been found on either bank than in the center of the channel (Figure 33). This is probably due to the high degree of scouring and substrate instability in the center of the channel. Results from the bank sites show sampling the left bank of the Sacramento River (D4L) provides the best opportunity for detection of a species in this region.

The third benthic sampling region includes one site in the western delta (D11-C) and three sites in the central delta (D19-C, D28A-R, D28A-L) (Figure 33). Comparisons of species occurrence among these sites show more species have been found in the banks of Old River (D28A-L, D28A-R) than in either of the lacustrine sites (D11-C, D19-C). Of the two sites on Old River, D28A-L provides a slightly better

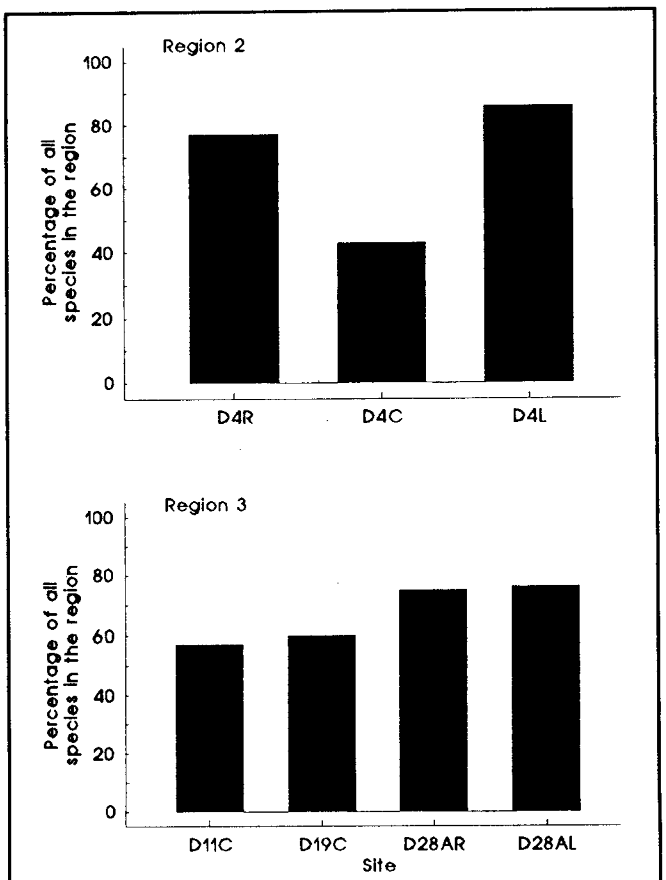


Figure 33
SIMILARITY IN BENTHIC SPECIES COMPOSITION AMONG SITES IN TWO DELTA REGIONS

chance of collecting a higher diversity of benthic species.

These results are limited by the relatively few sites sampled in each region or, in many cases, the complete lack of sites in a region. Ideally, one or more sites should be sampled in each environmentally distinct region within the delta and Suisun Bay. This distribution of sampling effort would yield more ecologically relevant information necessary in determining environmental factors that regulate the abundance and distribution of benthic organisms in the upper estuary.

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